**U.S. DEPARTMENT OF COMMERCE**
**National Technical Information Service**

N77-78624

# Proceedings of the Conference on Waste Heat Management and Utilization, Held at Miami Beach, Florida on May 9-11, 1976. Volume I

(U.S.) National Aeronautics and Space Administration, Washington, DC

**Prepared for**

Nuclear Regulatory Commission, Washington, DC

1976

NASA-TM-X-74100-vol. I

GREAT SEAL UNIVERSITY OF MIAMI CORAL GABLES FLORIDA 1925

NASA
National Aeronautics and
Space Administration

UNITED STATES NUCLEAR REGULATORY COMMISSION

UNITED STATES ENVIRONMENTAL PROTECTIO

CITIZENSHIP
DUKE POWER
SERVICE

FPL
FLORIDA POWER & LIGHT COMPANY

VOL. 1

# WASTE HEAT MANAGEMENT AND UTILIZATION

(NASA-TM-X-74100-Vol-1) PROCEEDINGS OF THE
CONFERENCE ON WASTE HEAT MANAGEMENT AND
UTILIZATION, VOLUME 1 (National Aeronautics
and Space Administration) 427 p
00/45
N77-78624
THRU
N77-78643
Unclas
31216

Editors:
SAMUEL S. LEE
SUBRATA SENGUPTA

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

# PROCEEDINGS OF THE CONFERENCE ON WASTE HEAT MANAGEMENT AND UTILIZATION

9 – 11 May, 1976
Miami Beach, Florida

Presented by:
Department of Mechanical Engineering,
University of Miami

Sponsored by:
National Aeronautics and Space Administration NASA
United States Nuclear Regulatory Commission NRC
United States Environmental Protection Agency EPA
Duke Power Company
Florida Power and Light Company
School of Continuing Education, University of Miami

In Cooperation with:
American Society of Mechanical Engineers
Miami Section

Editors:
Samuel S. Lee, University of Miami
Subrata Sengupta, University of Miami

1<

## ACKNOWLEDGEMENTS

The Conference Committee gratefully acknowledges the support of the Keynote Speaker, Mr. Frank Staszesky. It also greatly appreciates the help of the Conference Banquet Speaker, Dr. Robert Uhrig.

Gratitude is also expressed to all the authors and speakers who made this conference a worthwhile endeavour in scientific communication.

The Session Chairmen and Co-Chairmen deserve special thanks for organizing and conducting the technical sessions.

The support of the numerous students and faculty of the University of Miami is gratefully acknowledged.

The invaluable help of the scientists and administrators of the sponsoring organizations was a key element in making this conference comprehensive. We express our sincerest gratitude to them.

Conference Committee
Miami, May, 1977

2<

## CONFERENCE COMMITTEE

Dr. Samuel S. Lee:
*Conference Chairman*
Chairman, Department of Mechanical Engineering,
University of Miami

Dr. Subrata Sengupta:
*Conference Co-Chairman and Coordinator*
Department of Mechanical Engineering,
University of Miami

Mr. Roy A. Bland:
Earth Resources Branch
National Aeronautics and Space Administration,
Kennedy Space Center

Mr. Frank Swanberg:
Health and Environmental Research Branch
United States Nuclear Regulatory Commission

Dr. Theodore G. Brna:
Emmission Effluent Technology Branch,
Utility and Industrial Power Division,
United States Environmental Protection Agency

Mr. Charles A. Dewey:
Civil-Environmental Division,
Duke Power Company

Mr. Charles Henderson:
Environmental Division,
Florida Power and Light Company

## CONFERENCE SUPPORT

Arrangements:
Tony Pajares,
Lois Rosenzweig:
The School of Continuing Studies

Special Assistants:
Peter Kondis
Carol Glaze
Mary Rivera
Sally Pendleton

This publication is available at a cost of $55.00 from:
Mechanical Engineering Department
University of Miami
Coral Gables, Florida 33124

# FOREWORD

In the United States, at present, approximately 350,000 MW of steam generating capacity is in the design or construction phase. This is about 80% of all the existing electrical powers generation capacity at the end of 1973. Compounding this trend is the possibility of 5 GW (5000 MW) energy parks which may become reality in the next decade. The possible environmental consequences need serious study. Considering, that for every unit of energy converted to electricity two units are rejected as waste heat, there is a need for utilization efforts.

While the present energy crisis has brought to focus the finite resources of our planet, it is essential to perpetuate the realization that our planet is a finite sink. It is, therefore, imperative to optimize the energy-environment-economy system in an integrated manner.

This conference was organized to provide a forum for inter-disciplinary exchange. The widely scattered biological, economic and engineering state-of-the-art knowledge could then be compiled into a single source, namely, the conference proceedings.

The conference gave equal emphasis to pollution abatement and utilization. Waste heat may come to be regarded as an important energy resource. This document, it is hoped, will serve the stated objectives.

Samuel S. Lee, Chairman
Subrata Sengupta, Co-Chairman

A partial listing of contents includes:

## CONTENTS

## WASTE HEAT MANAGEMENT AND UTILIZATION CONFERENCE

### VOLUME I

Page No.

GENERAL SESSION (Session 1) 1-1

EPA VIEWS ON WASTE HEAT MANAGEMENT AND UTILIZATION 1-3
D. J. Graham, Environmental Protection Agency, Washington, D.C.

THE ROLE OF MODELING IN THE ASSESSMENT OF THERMAL POWER PLANT COOLING SYSTEM ON AQUATIC ENVIRONMENTS 1-13
R. A. Goldstein, J. Maulbetsch, R. Wyzga, Electric Power Research Institute, Palo Alto, California

PHYSICAL IMPACT OF WASTE HEAT DISPOSAL 1-15
S. S. Lee, S. Sengupta, University of Miami, Coral Gables, Florida

THE ANSWER IS BIOLOGICAL 1-17
D. Dunlop, Florida Power & Light, Miami, Florida

STANDARDS (Session 2A) 2A-1

AN APPROACH TO THERMAL WATER QUALITY STANDARDS 2A-3
C. Jeter, S. C. Department of Health & Environmental Control, Columbia, South Carolina

PROPOSED ANSI GUIDE FOR AQUATIC ECOLOGICAL SURVEYS AT THERMAL POWER PLANTS 2A-7
R. Hartman, Envirosphere Company, Norcross, Georgia

THERMAL GUIDELINES AS THEY APPLY TO THE STEAM ELECTRIC POWER GENERATING INDUSTRY 2A-12a
R. Schaffer, U. S. Environmental Protection Agency, Washington, D.C.

EVALUATING THE ADVERSE IMPACT OF COOLING WATER INTAKE STRUCTURES ON THE AQUATIC ENVIRONMENT 2A-25
S. Bugbee, U.S. Environmental Protection Agency, Washington, D.C.

Page No.

ECOLOGICAL EFFECTS I (Session 2B) 2B-37

TEMPERATURE INFLUENCES ON GROWTH OF AQUATIC ORGANISMS 2B-39
C. Coutant, Oak Ridge National Laboratory, Oak Ridge, Tennessee

COMPARISON OF ENVIRONMENTAL EFFECTS DUE TO OPERATION OF BRACKISH AND/OR SALT WATER NATURAL & MECHANICAL DRAFT COOLING TOWERS 2B-41
S. Laskowski, Picard, Low & Garrick, Inc., Washington, D.C.

A SYSTEMS APPROACH TO BIOLOGICAL AND THERMAL CONSIDERATIONS IN COOLING LAKE ANALYSES 2B-69
K. Robinson, R. W. Beck & Associates, Denver, Colorado

BIOLOGICAL EFFECTS OF THERMAL EFFLUENT FROM THE CUTLER POWER PLANT IN BISCAYNE BAY, FLORIDA 2B-91
H. J. Teas, R. C. Smith, University of Miami, Coral Gables, Florida

COOLING SYSTEM I (Session 2C) 2C-108

PROBLEMS OF DRY COOLING 2C-109
F. K. Moore, Cornell University, Ithaca, New York

WATER CONSERVATION AND WET-DRY COOLING TOWERS IN POWER PLANT SERVICE 2C-137
M. W. Larinoff, Hudson Products Corporation, Houston, Texas

MODIFICATIONS TO ONCE-THROUGH COOLING WATER DISCHARGE STRUCTURE TO ACHIEVE ENTRAINMENT MIXING AND LATERAL TRANSPORT OF THERMAL PLUMES 2C-139
D. E. Miller, Alabama Power Company, Birmingham, Alabama

DRY COOLING FOR POWER PLANTS: INCENTIVES, PROBLEMS AND RESEARCH/DEVELOPMENT ACTIVITIES 2C-170 a
B. M. Johnson, Battelle-Northwest Laboratories, Richland, Washington; J. S. Maulbetsch, Electric Power Research Institute, Palo Alto, California

COMPARISON OF ALTERNATIVE DIFFUSER DESIGNS FOR THE DISCHARGE OF HEATED WATER INTO SHALLOW RECEIVING WATER 2C-171
E. E. Adams, K. D. Stolzenbach, Massachussets Institute of Technology, Cambridge, Mass.

Page No.

SOCIAL AND LEGAL ASPECTS (Session 3A) 3A-1

WASTE HEAT MANAGEMENT AND REGULATORY PROBLEMS 3A-3
W. L. Porter, Duke Power Company, Charlotte North Carolina

SOCIAL ASPECTS OF REGULATING WASTE HEAT 3A-15
V. DePass, C. Newman, Consolidated Edison Company of New York, Inc., New York City, N.Y.

SOCIAL ASPECTS OF THERMAL DISCHARGES FROM POWER PLANTS 3A-33
R. S. Thorsell, Edison Electric Institute, New York City, New York

SCIENTISTS, ENGINEERS, AND LAWYERS: THE PHENOMENON OF INTERDISCIPLINARY UNDERSTANDING 3A-35
B. Shanoff, Environmental Protection Agency, Washington, D.C.

ECOLOGICAL EFFECTS II (Session 3B) 3A-51

THE USE OF BIOLOGICAL/CHEMICAL INVESTIGATIONS FOR MANAGING THERMAL EFFLUENTS 3A-53
K. I. Kahl-Madsen, The Water Quality Institute, Denmark

POWER GENERATION: EFFECTS ON THE AQUATIC ENVIRONMENT IN MASSACHUSETTS 3A-55
R. A. Isaac, Massachusetts Division of Water Pollution Control, Westborough, Massachusetts

AVOIDANCE OF THERMAL EFFLUENT BY JUVENILE CHINOOK SALMON (ONCORHYNCHUS TSHAWYTSCHA) AND ITS IMPLICATIONS IN WASTE HEAT MANAGEMENT 3A-73
R. H. Gray, Battelle Pacific Northwest Laboratories, Richland, Washington

THE BIOLOGICAL IMPACT OF THERMAL DISCHARGE EXCEEDING 95°F - A CASE STUDY OF ALLEN STEAM STATION, NORTH CAROLINA 3A-87
D. W. Anderson, A. Gnilka, Duke Power Company, Charlotte, North Carolina

COOLING SYSTEMS II (Session 3C) 3C-113

COMPUTER ANALYSIS OF HEAT REJECTION SYSTEMS FOR COAL CONVERSION PROCESSES 3C-115
T. E. Eaton, C. E. Duncan, University of Kentucky, Lexington, Kentucky

Page No.

STRATEGIES FOR WASTE HEAT MANAGEMENT OF ONCE-THROUGH COOLING SYSTEMS 3C-119
B. Sill, Clemson University, Clemson, South Carolina

THERMAL IMPACT REDUCTION BY DILUTION, BIG BEND STATION, TAMPA, FLORIDA 3C-143
W. J. Johnson, Tampa Electric Company, Tampa, Florida

WET/DRY COOLING FOR WATER CONSERVATION 3C-163
G. A. Englesson, M. C. Hu, United Engineers, Philadelphia, Pennsylvania; W. C. Savage, U.S. ERDA, Washington, D.C.

OPTIMIZATION OF DRY COOLING SYSTEMS FOR 1000 MW FOSSIL FUEL POWER PLANTS 3C-193
J. Fake, T. Rozenman, PFR Engineering Systems, Inc., Marina del Rey, California

NUMERICAL MODELING I (Session 4A) VOLUME II 4A-1

NUMERICAL MODELS IN COOLING WATER CIRCULATION STUDIES: TECHNIQUES, PRINCIPLE ERRORS, PRACTICAL APPLICATIONS 4A-3
G. S. Rodenhuis, Danish Hydraulic Institute, Horsholm, Denmark

PREDICTION OF TEMPERATURE RESULTING FROM ONCE-THROUGH COOLING OF A 5000 MWe POWER STATION ALONG AN ESTUARY 4A-21
H. Ligteringen, Delft Hydraulics Laboratory, Delft, The Netherlands

A 3-DIMENSIONAL FREE SURFACE MODEL FOR THERMAL PREDICTIONS 4A-23
S. Lee, S. Sengupta, C. Tsai, H. Miller, University of Miami, Coral Gables, Florida

A SYSTEMATIC APPLICATION OF TRANSIENT, MULTI-DIMENSIONAL MODELS FOR COMPLETE ANALYSIS OF THERMAL IMPACT IN REGIONS WITH SEVERE REVERSING FLOW CONDITIONS 4A-43
A. H. Eraslan, Oak Ridge National Laboratory, Oak Ridge, Tennessee

REMOTE SENSING (Session 4B) 4B-53

AERIAL REMOTE SENSING OF THERMAL PLUMES 4B-55
R. A. Bland, NASA, Kennedy Space Center, Florida; H. Hiser, S. Lee, S. Sengupta, University of Miami, Coral Gables, Florida

Page No.

METEOROLOGICAL SATELLITES 4B-66a
M. Tepper, N. Durocher, NASA Headquarters, Washington, D.C.

THE LANDSAT PROGRAM 4B-67
H. Mannheimer, NASA Headquarters, Washington, D.C.

SEASAT SATELLITE 4B-77
W. McCandless, NASA Headquarters, Washington, D.C.

COST EFFECTIVE THERMAL MONITORING FOR STATE & LOCAL ACTIVITIES 4B-103
C. E. James, U.S. Environmental Protection Agency, Washington, D.C.

COOLING SYSTEMS III (Session 4C) 4C-106

THE THERMAL PERFORMANCE CHARACTERISTICS OF LARGE SPRAY COOLING PONDS 4C-107
R. D. Baird, D. M. Myers, Ford, Bacon & Davis Utah, Inc.; A. Shah, Spray Engineering Company, Salt Lake City, Utah

FIELD STUDY OF MECHANICAL DRAFT COOLING TOWER PLUME BEHAVIOR 4C-119
C. H. Goodman, E. Champion, Southern Company Services, Inc., Birmingham, Alabama; P.R. Slawson, Envirodyne Limited, Waterloo, Ontario, Canada

ATMOSPHERIC SPRAY - CANAL COOLING SYSTEMS FOR LARGE ELECTRIC POWER PLANTS 4C-121
R. W. Porter, S. Chaturvedi, Illinois Inst. of Technology, Chicago, Illinois

DRY/WET COOLING TOWERS WITH AMMONIA AS INTERMEDIATE HEAT EXCHANGE MEDIUM 4C-163
B. M. Johnson, R. T. Alleman, G. C. Smith, Battelle Pacific Northwest Laboratories, Richland, Washington

A COMPUTERIZED ENGINEERING MODEL FOR EVAPORATIVE WATER COOLING TOWERS 4C-180a
J. E. Park, Union Carbide Corporation, Oak Ridge, Tennessee

MANAGEMENT ASPECTS (Session 5A) 5A-1

HOW TO GET WASTE HEAT MANAGED 5A-1a
W. M. Rohrer, K. G. Kreider, University of Pittsburgh, Pittsburgh, Pennsylvania

Page No.

RESOURCE RECOVERY MODELS FOR REGIONAL PLANNING AND POLICY EVALUATION 5A-3
E. B. Berman, The Mitre Corporation, Bedford, Massachusetts

SELECTION OF ALTERNATIVE COASTAL LOCATIONS 5A-29
H. Schroder, Danish Hydraulic Institute, Horsholm, Denmark

USE OF ENVIRONMENTAL DATA FOR DETERMINING CONDENSER WATER SYSTEM ALTERNATIVES 5A-45
L. P. Beer, Roy F. Weston, Inc., West Chester, Pennsylvania

ECONOMIC ASPECTS (Session 5B) 5B-67

AN OPERATIONAL PROCEDURE FOR PREDICTING THE MOST ECONOMICAL USE OF CONDENSER COOLING MODES 5B-69
R. Waldrop, W. L. Harper, Tennessee Valley Authority, Norris, Tennessee

ECONOMICS OF BOILER BLOWDOWN WASTE HEAT RECOVERY 5B-81
M. R. Bary, Commonwealth Associates, Inc., Jackson, Michigan

MATHEMATICAL MODELING OF WASTE HEAT MANAGEMENT ALTERNATIVES FOR THE UNITED STATES 5B-83
H. J. Plass, University of Miami, Coral Gables, Florida

ENGINEERING TRADEOFFS GOVERNING WASTE HEAT MANAGEMENT AND UTILIZATION 5B-107
S. J. Daugard, T. R. Sundaram, Hydronautics, Inc., Laurel, Maryland

ENERGY RECOVERY THROUGH UTILIZATION OF THERMAL WASTES IN AN ENERGY-URBAN-AGROWASTE COMPLEX 5B-109
G. J. Trezek, L. F. Diaz, University of California at Berkeley, Berkeley, California

UTILIZATION (Session 5C) 5C-131

AN OVERVIEW OF WASTE HEAT MANAGEMENT IN TVA 5C-133
P. A. Krenkel, et al, Tennessee Valley Authority, Chattanooga, Tennessee

UTILIZATION OF POWER PLANT WASTE HEAT FOR HEATING 5C-157
R. W. Timmerman, Consultant, Boston, Mass.

Page No.

HEATING OF GREENHOUSES WITH TEPID WATER — 5C-177
A Fourcy, M. Dumont, A. Freychet, Instiut de Recherche Fondamentale, France

WASTE HEAT USE IN A CONTROLLED ENVIRONMENT GREENHOUSE — 5C-187
E. R. Burns, R. S. Pile, C. E. Madewell, Tennessee Valley Authority, Muscle Shoals, Alabama

UTILIZATION OF WASTE HEAT FROM POWER PLANTS BY SEQUENTIAL CULTURE OF WARM AND COLD WEATHER SPECIES — 5C-213
C. R. Guerra, B. L. Godfriaux, Public Service Electric and Gas Company, Newark, New Jersey

UTILIZATION II (Session 6A) — 6A-1

EXPERIENCE WITH A COMPUTER-BASED STUDY ON WASTE HEAT USAGE FOR INTEGRATED AGRICULTURAL PURPOSES IN MICHIGAN — 6A-3
I. P. Schisler, Michigan State University, East Lansing, Michigan

THE UTILIZATION OF WASTE HEAT FROM LARGE THERMAL POWER PLANTS — 6A-27
L. N. Reiss, Commonwealth Associates, Inc., Jackson, Michigan

USE OF WASTE HEAT FOR AQUACULTURE & AGRICULTURE IN CONJUNTION WITH A SURROGATE NUCLEAR ENERGY CENTER — 6A-29
R. K. Sharma, P. A. Merry, J. D. Buffington, S. W. Hong, and C. Luner, Argonne National Laboratory, Argonne, Illinois

INTEGRATED POWER, WATER AND WASTEWATER UTILITIES — 6A-31
J. P. Overman, C. W. Mallory, and H. M. Curran, Hittman Associates, Columbia, Maryland

NUMERICAL MODELING II (Session 6B) — 6B-32

COMPARISON OF PREOPERATIONAL HYDROTHERMAL PREDICTIONS AND OPERATIONAL FIELD MEASUREMENTS AT THREE NUCLEAR POWER PLANT SITES — 6B-33
G. S. Marmer, A. J. Policastro, Argonne National Laboratory, Argonne, Illinois

Page No.

THERMAL STRATIFICATION AND CIRCULATION OF WATER BODIES SUBJECTED TO THERMAL DISCHARGE — 6B-37
A. N. Nahavandi, M. A. Borhani, New Jersey Institute of Technology, Newark, New Jersey

A 3-DIMENSIONAL RIGID-LID MODEL FOR THERMAL PREDICTIONS — 6B-85
S. Sengupta, S. Lee, J. Venkata, C. Carter, University of Miami, Coral Gables, Florida

COOLING TOWER PLUMES (Session 6C) — 6C-115

SENSITIVITY ANALYSIS AND COMPARISON OF SALT DEPOSITION MODELS FOR COOLING TOWERS — 6C-117
T. Overcamp, G. W. Isreal, Clemson University, Clemson, South Carolina

VALIDATION OF SELECTED MATHEMATICAL MODELS FOR PLUME DISPERSION FROM NATURAL-DRAFT COOLING TOWERS — 6C-135
A. J. Policastro, B. A. Devantier, Argonne National Laboratory, Argonne, Illinois, R. A. Carhart, University of Illinois, Urbana, Illinois

IMPORTANT CONSIDERATIONS IN A SIMPLE NUMERICAL PLUME MODEL — 6C-137
L. D. Winiarski, Environmental Protection Agency, Corvallis, Oregon

UTILIZATION III (Session 7A) — 7A-1

PROSPECTS FOR THE UTILIZATION OF WASTE HEAT IN LARGE SCALE DISTRICT HEATING SYSTEMS — 7A-3
J. Karkheck, J. Powell, Brookhaven National Laboratory, Upton, New York

EXPLOITING NATURAL OYSTER POPULATIONS THROUGH WASTE HEAT UTILIZATION — 7A-27
B. J. Neilson, Virginia Institute of Marine Science, Gloucester Point, Virginia

USING HEATED EFFLUENT FROM A 835 MWe NUCLEAR POWER REACTOR FOR SHELLFISH AQUACULTURE — 7A-41
C. T. Hess, C. W. Smith, University of Maine, Orono, Maine

UTILIZATION AND DISSIPATION OF WASTE HEAT BY SOIL WARMING — 7A-73
D. R. DeWalle, Pennsylvania State University, University Park, Pennsylvania

Page No.

POTENTIAL RESEARCH PROGRAMS IN WASTE ENERGY UTILIZATION 7A-87
C. C. Lee, Environmental Protection Agency, Cincinnati, Ohio

NUMERICAL MODELING III (Session 7B) 7B-110

MODELING OF A HEATED PLUME DISCHARGE FOR COMPLIANCE WITH WATER QUALITY STANDARDS 7B-111
F. G. Ziegler, Aware, Inc., Nashville, Tenn.

MODEL FOR SHORE-ATTACHED THERMAL PLUMES IN RIVERS 7B-113
P. P. Paily, NALCO Environmental Sciences, Northbrook, Illinois and W. W. Sayre, Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa

SOME PRACTICAL ASPECTS OF THERMAL PLUME ANALYSIS 7B-135
L. L. Stookey, Manchester Laboratories, Inc. Manchester, Iowa

A LONGITUDINAL DISPERSION MODEL FOR SHALLOW COOLING PONDS 7B-143
M. Watanabe and G. H. Jirka, Massachusetts Institute of Technology, Cambridge, Mass.

COOLING SYSTEMS IV (Session 7C) 7C-145

COOLING WATER RESOURCES OF UPPER MISSISSIPPI RIVER FOR POWER GENERATION 7C-147
P. P. Paily, NALCO Envrionmental Sciences, Northbrook, Illinois, T. Y. Su, Sargent and Lundy Engineers, Chicao, Illinois, A. R. Giaquinta, J. F. Kennedy, Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa

INLAND FLORIDA COOLING SYSTEMS 7C-179
A. F. Dinsmore, Brown & Root, Inc., Houston, Texas

INVESTIGATION OF THE FLUID MECHANICAL BEHAVIOR OF A THERMAL STORAGE RESERVOIR FOR DRY COOLED CENTRAL POWER STATIONS 7C-209
M. Golay & E. C. Guyer, Massachusetts Institute of Technology, Cambridge, Mass.

Page No.

DISPERSION OF HEAT AND HUMIDITY FROM ATMOSPHERIC SPRAY COOLING SYSTEMS 7C-243
R. W. Porter, R. H. Weinstein, S. Chaturvedi, R. Kulik, J. Paganessi, Illinois Institute of Technology, Chicago, Illinois

RECENT RESEARCH IN DRY AND WET/DRY TOWERS 7C-285
L. R. Glicksman, Massachusetts Institute of Technology, Cambridge, Massachusetts

UTILIZATION IV (Session 8A) VOLUME III 8A-1

AN OVERVIEW OF WASTE HEAT UTILIZATION RESEARCH AT THE OAK RIDGE NATIONAL LABORATORY 8A-3
M. Olszewski, S. Suffern, C. C. Coutant, K. K. Cox, Oak Ridge National Laboratory, Oak Ridge, Tennessee

DRIFT FROM THE CHALK POINT NATURAL DRAFT BRACKISH WATER COOLING TOWER: SOURCE DEFINITION, DOWNWIND MEASUREMENTS, TRANSPORT MODELING 8A-25
R. O. Webb, G. O. Schrecker, D. A. Guild, Environmental Systems Corporation, Knoxville, Tennessee

A SIMULATION OF WASTE HEAT UTILIZATION FOR GREENHOUSE CLIMATE CONTROL 8A-57
F. P. Incropera & M. C. Freemyers, Purdue University, West Lafayette, Indiana

THERMAL CONTROL OF A SHALLOW POND WITH WASTE HEAT FROM A CLOSED CYCLE COOLING SYSTEM 8A-97
F. Incropera J. Rog, Purdue University, West Lafayette, Indiana

THE AGROTHERM RESEARCH PROJECT 8A-131
H. Luckow, A. Reinken,Thyssen House, Dusseldorf, Germany

PHYSICAL MODELS (Session 8B) 8B-133

THE DISCHARGE OF A SUBMERGED BUOYANT JET INTO A STRATIFIED ENVIRONMENT 8B-135
S. Ostrach, Case Western Reserve University, Cleveland, Ohio

Page No.

HYDRAULIC INVESTIGATIONS OF THERMAL DIFFUSION DURING HEAT TREATMENT CYCLES: SANONOFRE NUCLEAR GENERATING STATION UNITS II AND III — 8B-157
M. S. Isaacson, R. C. Y. Koh, E. J. List, California Institute of Technology, Pasadena, California

LABORATORY INVESTIGATION ON SOME FUNDAMENTAL ASPECTS OF THERMAL PLUME BEHAVIOR — 8B-181
T. R. Sundaram, E. Sambuco, S. Kapur, A. Sinnarwalla, Hydronautics, Inc., Laurel, Maryland

CASE STUDIES I (Session 8C) — 8C-183

SOME SOLUTIONS TO THERMAL PROBLEMS IN THE SOUTHEASTERN UNITED STATES — 8C-185
C. H. Kaplan, U.S. Environmental Protection Agency, Atlanta, Georgia

WASTE HEAT IN THE CEGB — 8C-197
P. F. Chester, Central Electricity Generating Board, Leatherhead, Surrey, England

THE EXCESSIVE BURDEN AND WASTE OF DUPLICATIVE REGULATION — 8C-217
J. H. Hughes, Commonwealth Edison, Chicago, Illinois

NUMERICAL & REMOTE SENSING STUDIES OF LAKE BELEWS AN ARTIFICIAL COOLING LAKE — 8C-229
B. McCabe, S. Sengupta, S. Lee, S. Mathavan, University of Miami, Coral Gables, Florida

UTILIZATION V (Session 9A) — 9A-1

THE SHERCO GREENHOUSE: A DEMONSTRATION OF THE BENEFICIAL USE OF WASTE HEAT — 9A-3
G. C. Ashley, J. S. Hietala, Northern States Power Company, Minneapolis, Minnesota

DECENTRALIZED ENERGY CONVERSION FOR WASTE HEAT UTILIZATION — 9A-17
J. R. Schaefgen, U.S. Department of Commerce, National Bureau of Standards, Washington,D.C.

WASTE HEAT EMPLOYMENT FOR ACCELERATED REARING OF COHO SALMON — 9A-19
E. Brannon, University of Washington, Seattle, Washington

Page No.

WASTE HEAT UTILIZATION FROM A UTILITY STANDPOINT: THE PROBLEM OF IMPLEMENTATION 9A-29
A. C. Gross, M. C. Cordaro, Long Island Lighting Company, Hicksville, New York

UTILIZATION OF WASTE HEAT FROM NUCLEAR POWER STATION FOR COMMUNITY SPACE CONDITIONING 9A-39
W. Steigelmann, Drexel University, Philadelphia, Pennsylvania

IMPACT ON WEATHER (Session 9B) 9B-41

ATMOSPHERIC EFFECTS OF WASTE HEAT DISSIPATED FROM LARGE POWER CENTERS 9B-43
C. M. Bhumralkar, J. A. Alich, Jr., Stanford Research Institute, Menlo Park, California

EVAPORATIVE COOLING POWER PLUMES: A REVIEW OF BEHAVIOR, PREDICTIONS, AND METEOROLOGICAL EFFECTS 9B-45
H. C. Benhardt, T.E. Eaton, University of Kentucky, Lexington, Kentucky

A NUMERICAL MODELING STUDY OF WASTE HEAT EFFECTS ON SEVERE WEATHER 9B-67
H. D. Orville, South Dakota, School of Mines and Technology, Rapid City, South Dakota

HEAT PLUMES OVER COOLING RESERVOIRS 9B-83
M. A. Estoque, H. P. Gerrish, University of Miami, Coral Gables, Florida

CASE STUDIES II (Session 9C) 9C-85

CASE STUDY - FLORIDA POWER AND LIGHT 9C-87
C. Henderson, Florida Power & Light Company, Miami, Florida

ASSESSING AND SOLVING ENRIONMENTAL PROBLEMS OF POWER PLANT COOLING: AN INTEGRATED APPROACH 9C-89
B. Chezar, R. H. Tourin, New York State Energy Research and Development Authority, New York, New York

THERMAL PLUME EVALUATION PROGRAM OF INDIAN POINT NUCLEAR POWER PLANT 9C-91
H. C. Moy, Consolidated Edison, New York, New York

Page No.

CASE STUDY: NEGOTIATION AND DEMONSTRATION DEVELOPMENT - 316A DEMONSTRATION TYPE II 9C-113
R. S. Schermerhorn, Impact - The Environmental Scientists & Engineers, Denver, Colorado

UTILIZATION VI (Session 10A) 10A-1

WASTE HEAT UTILIZATION FOR DEWATERING SEWAGE SLUDEGE 10A-3
R. E. Birner, A. Ernest, J. H. Schlinta, R. M. Manthe, Metropolitan Sewerage District of the County of Milwaukee, Milwaukee, Wisconsin

THERMODYNAMIC ANALYSIS OF RANKINE CYCLE ENERGY SYSTEMS UTILIZING WASTE HEAT 10A-25
C. D. Henry III, R. Fazzolare, University of Arizona, Tucson, Arizona

POWER PLANT WASTE HEAT - DISASTER OR BOON? 10A-33
K. S. Sunder Raj, Power Authority of the State of New York, New York, New York

WASTE HEAT UTILIZATION IN AQUACULTURE SOME FUTURISTIC AND PLAUSIBLE SCHEMES 10A-35
J. R. Wilcox, Florida Power & Light, Miami, Florida

IN-SITU DATA ACQUISITION (Session 10B) 10B-47

SUBMERGED MULTIPORT DIFFUSER THERMAL DISCHARGES FROM CONDEPTUAL DESIGN TO POSTOPERATIONAL SURVEY 10B-49
T. J. Tsai, B. E. Burris, Stone & Webster Engineering Corporation, Boston, Mass.

OBSERVATIONS OF THERMAL PLUMES FROM SUBMERGED DISCHARGES IN THE GREAT LAKES AND THEIR IMPLICATIONS FOR MODELING AND MONITORING 10B-71
J. D. Ditmars, R. A. Paddock, A. A. Frigo, Argonne National Laboratory, Argonne, Ill.

AN ANALYSIS OF THER THERMAL MONITORING DATA COLLECTED AT THE PEACH BOTTOM ATOMIC POWER STATION 10B-73
A. Witten, D. Gray, Oak Ridge National Laboratory, Oak Ridge, Tennessee

MODELING THE INFLUENCE OF THERMAL EFFLUENTS ON ECOSYSTEM BEHAVIOR 10B-103
K. I. Dahl-Madsen, The Water Quality Institute, Denmark

Page No.

MONITORING (Session 10C) 10C-105

STATE OF THE ART OF THERMAL MONITORING PROGRAMS IN THE POWER INDUSTRY 10C-107
J. Z. Reynolds, Consumers Power Company, Jackson, Michigan

EVALUATION OF ENVIRONMENTAL IMPACT PREDICTIONS 10C-119
P. A. Cunningham, Oak Ridge National Laboratory, Oak Ridge, Tennessee

THE QUALITY AND COST OF INFERENCES CONCERNING THE EFFECTS OF NUCLEAR POWER PLANTS ON THE ENVIRONMENT 10C-139
D. A. McCaughran, University of Washington, Seattle, Washington

THE STATE-OF-THE-ART OF ENVIRONMENTAL AND THERMAL PERFORMANCE MONITORING TECHNIQUES FOR CLOSED-CYCLE COOLING SYSTEMS 10C-159
G. O. Schrecker, K. R. Wilber, R. O. Webb, Environmental Systems Corporation, Knoxville, Tennessee

OPEN SESSION I (Session 11A) 11A-1

EFFECTS AND CONSEQUENCES OF POWER PLANT INDUCED MORTALITY ON THE SAN FRANCISCO BAY-DELTA STRIPED BASS POPULATION 11A-3
M. W. Lorenzen, Tetra Tech, Inc., Lafayette, California

SURFACE HEAT TRANSFER FROM A GEOTHERMALLY-HEATED LAKE 11A-43
A. Miller, Jr., Brigham Young University, Provo, Utah; R. L. Street, Stanford University, Stanford, California

PATTERNS OF THERMAL PLUME CONFIGURATION: IMPLICATIONS FOR ENVIRONMENTAL IMPACT ASSESSMENT AND RESOURCE MANAGEMENT 11A-63
R. C. Baird, Geo-Marine, Inc, Richardson, Texas

A STRIPED BASS MODEL FOR POWER PLANT EVALUATION 11A-87
C. W. Chen, Tetra Tech, Inc., Lafayette, California

Page No.

OPEN SESSION II (Session 11B) 11B-111

PREDICTION OF COMBUSTION CHARACTERISITCS FOR REFUSE-DERIVED FUEL (RDF) 11B-113
R. J. Schoenberger, J. Gibs, Drexel University; K. Sonsteby, Pennsylvania Power & Light Company; A. M. Arndt, Lehigh County Authority; R. M. Gruninger, Malcolm Pirie, Inc., Philadelphia, Penn.

MINNESOTA AERIAL INFRARED PROGRAM 11B-115
S. Stewart, Minnesota

INTEGRATED STEAM SYSTEMS FOR ELECTRIC POWER GENERATION FROM WASTE HEAT 11B-117
J. P. Davis, Energy Systems Thermoelectron Corporation, Waltham, Mass.

EFFECTS ON ECOSYSTEMS 11B-131
M. T. Masnick, U.S. Nuclear Regulatory Commission, Washington, D.C.

A COMPARISON OF THE BIOLOGICAL EFFECT OF HEATED EFFLUENTS FROM TWO FOSSIL FUEL PLANTS IN THE FLORIDA SUBSTROPICS: ONE EAST COAST, ONE WEST COAST 11B-133
A. Thorhaug, University of Miami, Coral Gables, Florida

## SESSION I
## GENERAL SESSION

1-45-12

# EPA VIEWS ON WASTE HEAT MANAGEMENT & UTILIZATION

D. J. GRAHAM
Environmental Protection Agency
Washington, D.C. U.S.A.

## ABSTRACT

The Environmental Protection Agency's research and development program that supports its thermal pollution abatement activity is described. Projects related to cooling water intake technologies, cooling tower drift, water treatment, and integrated assessments are discussed. Related activities, concerned with the beneficial use of waste heat, are described in terms of by-product waste heat utilization, by-product electrical generation by industry, and integrated energy complexes.

## INTRODUCTION

In 1972, Congress enacted amendments to the Federal Water Pollution Control Act that required a number of fundamental changes in the Nation's approach to achieving clean water. This Act required that technology-based effluent limitations be considered in the issuance of water discharge permits. Among other provisions, it generally required the use of best available technology to dissipate the heat produced in the generation of electric power. Although a section of the Act provides a limited exception allowing certain powerplants to meet a lesser standard, zero discharge was established as the national goal. Subsequent guidelines, proposed in 1974 by the Agency, found that this goal could only be met by a closed, recirculating cooling system. In the majority of cases this was intended to mean evaporative cooling towers.

Unfortunately, cooling towers are not without their drawbacks. Apart from their increased costs over once-through systems, they may also cause discharges to the environment in the form of toxic chemicals, mist or fog, and undesirable aerosol drift especially when seawater is used as a cooling medium. Despite the fact that makeup water volume requirements are but a few percent of those needed for open-cycle systems, evaporative losses in water-short areas can be great enough to dictate the use of more costly dry or combination wet/dry systems.

While initial steps to curtail the discharge of waste heat were being taken, the beneficial use of this waste heat was being increasingly viewed as an important conservation measure. Now, with natural gas in short supply and with overhanging uncertainty of foreign petroleum imports, the tremendous but elusive potential offered by this wasted energy appears even more attractive. Within EPA, we now see a convergence of interests to use this heat from three separate groups. Water pollution engineers would be grateful if waste heat was eliminated today; they seek zero thermal discharge. The air pollution people note that every wasted Btu saved represents a potential reduction in fossil fuel combustion, with a consequent reduction in air effluents. Resource conservation workers have calculated that if recent projections in electrical demand prove correct, the predicted heat dissipation from central power sources in the year 2000 will equal our total energy requirements in 1970 [1]--an attractive target for conservation, indeed.

To support the Federal Water Pollution Control Act, and the standard-setting process which the Act requires, the Agency undertakes research, development and demonstration programs in areas such as health effects, ecological effects, environmental processes and quality, environmental management, pollution control systems, and instrumentation. This work is accomplished to provide environmental information to establish the need for controls, to develop control technology if none is available, and to reduce the costs and secondary adverse environmental impacts from such controls. In addition, the Agency is active in promoting greater overall efficiency in the fossil fuel combustion area by supporting programs in low level heat use and cogeneration.

Since fiscal year 1975, EPA's Office of Energy, Minerals, and Industry has coordinated a Federal Energy/Environment Research and Development program that is conducted by seventeen government agencies. In the material that follows, a brief overview of the interagency program in waste heat management and utilization, and a discussion of recent trends in that program, will be presented.

## INTAKE TECHNOLOGIES

Although considerable work on thermal effects in both marine and fresh water continues to be supported, direct mortality of important organisms due to thermal discharges is now thought to be of less quantitative significance than was once believed [2]. As a consequence, our thermal effects work has been expanded and broadened to include projects such as studies of the effect of temperature on marine invertebrate behavior. Feeding activity, shelter dependence, and social interactions are typical areas of investigation. Recent studies have also disclosed that the passage of organisms in cooling water through the power plant system, rather than direct thermal effects, is often a major causative factor in aquatic organism mortality [3]. In cooperation with the Tennessee Valley Authority, a state-of-the-art report on intake technologies has been published to address the problem of reducing fish losses at both large-volume, once-through cooling water intakes and lower-volume intakes at plants requiring only makeup water [4]. Many types of behavioral barriers have been tested for their capability of guiding fish away from water intakes. To date, most have limited applicability to power plant intakes although several successful applications of electrical, air, and louver barriers have been reported.

Additional related study and development is needed in the following areas:

(1) Prediction of fish losses and impact at proposed intake site,

(2) Development of methods to divert from, guide or otherwise control the movement of fish past water intakes. Studies inherent in this development include fish response to velocity and temperature gradients, as well as other stimuli,

(3) Protection of larval fish and eggs at water intakes from entrainment and entrapment using fine mesh screening, filtration devices, and low velocity slotted and perforated conduit, and other mechanisms.

In partial response to these research needs, the EPA hopes to support the field evaluation of promising intake structures which prevent or reduce the entrapment and entrainment of aquatic organisms. This work, if undertaken, should be completed by early 1980. In addition, on-going work at the Oak Ridge National Laboratory to study physical damage to plankton from abrasion and pressure changes during cooling system passage will continue to be supported by EPA through our cooperative interagency program.

## COOLING TOWERS AND AEROSOL DRIFT

Scarce fresh water resources make future consideration of brackish and seawater as cooling media highly important. Nevertheless, the current knowledge of potential environmental impact of saline aerosol drift from cooling towers, spray modules, and cooling canals is very incomplete.

In response to a direct request from the Office of Enforcement, EPA's Corvallis Environmental Research Laboratory initiated a study in 1973 to assess the terrestrial ecological effects of aerosol drift from salt water mechanical cooling devices being tested at the Florida Power and Light nuclear power plant complex at Turkey Point, Florida [5].

A final report of this study was recently distributed. Indigenous vegetation, soil and fresh water samples were taken over a year-long period to acquire pre-activation baseline data and to provide for the assessment of possible environmental impact of salt aerosol loading from the test cooling devices. Results have shown that no measurable effects were detected on indigenous plants as a consequence of the test cooling operation. In addition to indigenous plants, bush bean and sweet corn plants were introduced at Turkey Point. These cultivars showed visible foliar injury and high salt concentrations only at the exposure site closest to the cooling modules (215 meters).

The results of this work is encouraging. However, much additional research must be undertaken before salt water cooling systems are fully accepted. A related cooperative project jointly sponsored by the Electric Power Research Institute, the Energy Research and Development Administration, the state of Maryland, and EPA is currently investigating brackish water cooling tower drift at the Potomac Electric Power Company's Chalk Point plant. The impact of an average 14,000 ppm saline drift on local tobacco crops is of major concern.

In water scarce areas, consideration is being given to providing cooling tower makeup from sewage treatment plant discharge and irrigation runoff. In assessing the feasibility of this source of makeup, the possibility of transmitting pathogens and toxic materials must be considered. A recently initiated project with EPA support is concerned with possible adverse drift from a cooling tower using sewage plant effluent as a water source.

Two cooling tower projects have recently been completed by EPA and final reports should be available soon. The first project involved a design cost study for wet/dry tower systems used in conjunction with 1000 MWe coal-fired power plants to reject waste heat while either conserving water or minimizing ground fogging. The second project involved the development of a methodology and techniques for evaluating the performance and economics of dry cooling systems.

## WATER TREATMENT

Several water recycle and reuse options are now being studied by our laboratory in Research Triangle Park for five specific power plants in various regions of the country. These options include measures such as increasing the number of cycles for cooling tower water, using cooling tower blowdown to sluice coal ash to the disposal site, and closing the loop (zero discharge) on the ash disposal system. A selected option will eventually be demonstrated on a pilot scale, or possibly full scale, at one or more power plants. This technology should minimize water consumption and concentrate waste streams in an attempt to achieve zero discharge. A detailed approach to the application of the recycle/reuse concepts to a variety of power plant situations will be developed and reported after completion of the demonstration(s).

Waste stream treatment methods to enhance recycle/reuse, lower costs, and render acceptable those streams which require discharge are also being developed. Magnesium carbonate softening of cooling tower makeup water promises to decrease cooling tower blowdown over conventional treatment methods at a greatly reduced cost; assessment of this process will be completed during 1978. A vertical tube evaporator with interface enhancement is being studied for treating cooling tower blowdown. The TVA, through our cooperative interagency program, is continuing to evaluate waste stream treatment by reverse osmosis and ultrafiltration; both methods are economical and energy conserving.

Studies of alternatives to chlorine for control of condenser fouling are continuing; bromine chloride is being studied on a full scale plant. Organo-tin polymer coatings for condenser tubes are also being evaluated. These studies will support development and implementation of effluent guidelines for power plants.

## INTEGRATED TECHNOLOGY ASSESSMENTS

During the past decade the field of pollution research has matured beyond the phase of simply demonstrating adverse environmental effects from thermal discharges and developing control technologies. We are now in a more difficult period of also assessing the risk associated with particular man-made developments. For example, the well known Seabrook Nuclear Power Plant controversy underscores the need for a better understanding of ecosystem damage and the probable social impact resulting from a complex engineering activity. Current knowledge of direct biological effects, while extensive, does not permit our comprehension of what these combined effects mean in terms of human welfare or significant damage to ecological systems.

Because of this, the EPA is undertaking integrated assessments and other studies to identify environmentally, socially, and economically acceptable energy development alternatives. One such study, now underway, will provide an integrated technology assessment of electric utility energy systems [6]. This project has the following objectives:

(1) To provide for formulation and testing of pollution control policies and strategies with respect to the utility industry which addresses current and near term issues,

(2) To identify those issues, especially environmental issues, which are likely to require policy decisions in the future,

(3) To identify the research programs which should be initiated to provide a sound basis for future decisions regarding these issues.

Although the first year of this study (just completed) has focused primarily on air pollutants, we are currently studying the analysis effort required to examine in depth on a regional and national scale the chemical and thermal releases from power plants. It is especially important to analyze the interactive effects on water quality of these two types of residuals and their respective control technologies.

## WASTE HEAT UTILIZATION

The EPA has been involved in waste heat reduction and control activities primarily because of its overall mandate to reduce environmental impacts. From an environmental viewpoint, waste heat utilization offers numerous benefits. Waste heat utilization can:

(1) Reduce the quantity of pollutant generation and release,

(2) Reduce the cost of pollution control equipment,

(3) Offer potential revenue which could help offset cost of pollution control,

(4) Conserve energy resources, and,

(5) Eliminate the overall impact of obtaining, processing and supplying the energy which has been replaced by the "reclaimed" heat and reduce residues from the energy transformation process.

There are numerous options available for waste heat utilization/reduction, many of which have received attention in EPA's program and others which will be described during this conference. To date, EPA's focus has been on three options which are believed to have good potential for application [7]:

(1) Utilization of by-product waste heat discharged from conventional industrial and utility plants for agriculture and aquaculture,

(2) Generation of by-product electricity in industrial plants, and,

(3) Development of integrated energy production/use complexes which utilize energy more efficiently.

The first option uses heat after it has been discharged from a process or facility, while the others involve optimizing the design and management of the process itself to reduce the amount of heat wasted.

26<

## By-Product Waste Heat Utilization

This option has the greatest potential for near-term (through 1985) energy savings, and most waste heat applications studied to date are based on this approach. The waste heat involved is the conventional, by-product heat rejected to air or water from an electric utility or industrial process. Typically, it is low-quality heat, such as that available in power plant condenser cooling water which is usually between 5-22 °C (9-40°F) above incoming water temperature.

A number of direct-use waste heat applications have been investigated to varying degrees--the more promising methods receiving effort toward demonstrating their full-scale feasibility. Prior to the energy crisis of 1973, the most economically attractive waste heat applications were in agricultural and aquacultural endeavors.

Agricultural demonstrations have shown promise in areas of irrigation, frost protection, subsoil heating, and greenhouse heating and climate control. Greenhouse applications appear the most economical ones, because high-cash-value crops, such as selected flowers and vegetables, are involved. Refined systems are currently being demonstrated which should result in commercial involvement in 3 to 4 years.

EPA helped support an agricultural project near Eugene, Oregon, from 1968 to 1973. Cooling water from a pulp and paper mill was used to provide spring frost protection, irrigation, crop cooling in the summer, and soil heating. The project was very successful in providing spring frost protection for field crops and in increasing greenhouse crop yields with heating by underground pipes.

A second demonstration project partially funded by EPA is now underway at the Sherburne County power plant in Becker, Minnesota. Heated water from the condenser cooling loop of the 2-unit, 1400 MWe plant will provide soil and air heating for a one-half acre greenhouse, an operation that normally consumes 25,000 gallons of oil or 3.5 million cubic feet of natural gas a year. If the experiment is an economic success, a commercially developed 100-acre greenhouse complex could be in operation by 1985, at a savings of 5 million gallons of oil or 700 million cubic feet of gas.

The Tennessee Valley Authority has received funds from EPA to use waste heat to stimulate the growth of algae and amur fish in a project designed to recycle nutrients from livestock operations. The project will use livestock wastes to grow algae which will subsequently be fed to amur fish. The amur will then be harvested for livestock food.

Numerous other systems have been proposed or are under development for utilizing low-level waste heat in water. Projects that involve stimuulation of biological growth have shown the most promise for development.

These include aquaculture, mariculture, algae production for animal food, and biological waste-treatment processes. Additional work, however, is needed to identify species of plants and animals which respond most favorably to waste heat stimulation and to adequately control the chemical and biological wastes from these activities. Since they have potential for highly efficient protein production, these processes can also be expected to supplement conventional but energy-intensive agricultural practices.

Efforts are also underway to identify, develop and demonstrate by-product heat recovery situations within industries which discharge the waste in either water or air streams. Some process-specific applications have already been identified and are nearing demonstration through support of EPA's industrial energy conservation program.

## By-Product Electrical Generation by Industry

This option has a good potential for the mid-term (1985 through 2000) reduction of waste heat. Nearly 20 percent of the Nation's primary fuel is used to produce industrial steam, only 30 percent of which is used to generate electrical power before being used for process heating. Most industrial facilities generate their own process steam in a natural gas or oil-fired package boiler and purchase electricity from utilities. Package boilers have been employed rather than field-erected boilers because of their low capital cost, relative simplicity of operation, and the availability of low-cost natural gas and oil. Package boilers usually operate at low steam pressure (below 400 psia) at an operating efficiency of about 75 percent. Field-erected boilers, on the other hand, are more expensive to buy and more complex to operate, but have the capability of operating at higher pressures (with efficiencies up to 88 percent) and with lifetimes twice as long.

Potentially, more than 33,000 MWe of additional power could be generated by industrial by-product power units by 1985, resulting in an equivalent savings of 680,000 barrels per day of oil. It is estimated that this could be achieved with a return on investment of 20 percent or more per year.

This application has the potential to reduce the environmental impact of thermal and air pollutants, conserve fuel, lower the overall capital needed for electrical generation, and reduce the cost of producing power and process steam. On the debit side, non-utility industries will be required to generate capital for new facilities and will need to upgrade the skills of the boiler plant personnel. However, as the cost of energy continues to rise, it is likely that industries will find that the incentives outweigh the disadvantages. EPA is assessing the technical and economic feasibility of this concept as well as the environmental benefits to be derived from its adoption.

The Federal Energy Administration is currently funding a study of industrial dual-purpose power plant development [8]. The EPA and other Federal agencies are monitoring this effort and are providing input data in their areas of expertise. Although concentration is on process industries, and not the steam electric power utilities, this effort could prove to be a stimulus for the widespread use of waste heat. Specific barriers to such use and suggested Federal action to reduce these barriers are being identified and evaluated. For example, an environmentally-related barrier would be the potential prohibition of increased fossil fuel combustion in a non-attainment air district.

Research efforts such as these tend to confirm the inevitability of widespread actions, both public and private, to put waste heat to productive use on a meaningful scale.

## Integrated Energy Production/Use Complexes

This option has the potential for waste heat utilization/reduction over the long-term (post-2000). In this application, production and use facilities are designed for operational compatability in terms of energy form, load characteristics, and equipment lifetime. They provide opportunities for increasing the efficiency of energy utilization by 10 to 15 percent. These facilities, however, must be large to interest utilities in a joint venture.

Few integrated energy facilities have been built in the U. S. because of incompatibility of production and user systems, financial risk, lack of necessary capital, and inappropriate long-term planning. Opportunities for waste heat utilization include district heating, off-peak storage and on-peak use for electrical power and heating application; industrial process heating; and a combination of these options. Hopefully, the potential economic incentives induced by rising fuel costs and public concern for more efficient utilization of energy resources will encourage industry, utilities, and government to solve problems which now limit development of integrated energy facilities.

## SUMMARY

In summary, the Environmental Protection Agency has several objectives that are met by the efficient and effective management of waste heat or --more importantly--by the beneficial use of rejected heat. We, and other organizations, are continuing our research efforts in areas of promise. The ultimate solution to waste heat and other societal problems requires cooperation between the academic, private and public sectors to reach common goals. This conference is an important step in that direction.

## References

1. U.S. Energy Research and Development Administration, "A National Plan for Energy Research, Development, and Demonstration," ERDA-48, June 1975.

2. Franklin, R.E., et al, "Participation of ERDA in the Transport and Ecological Effects Categories of the Pass-Through Program," In Proceedings: National Conference on Health, Environmental Effects, and Control Technology of Energy Use. Environmental Protection Agency 600/7-76-002, February 1976.

3. Coutant, C.C., "How to Put Waste Heat to Work," Environmental Science and Technology, Vol. 10, Page 868, September 1976.

4. Ray, S.S., et al, "A State-of-the-Art Report on Input Technologies," Environmental Protection Agency 600/7-76-020, October 1976.

5. Hindarvi, I.J., et al, "Ecological Effects of Aerosol Drift From a Saltwater Cooling System," Environmental Protection Agency 600/3-76-078, July 1976.

6. Plotkin, S.E., "EPA's Integrated Assessment Program," In Proceedings: National Conference on Health, Environmental Effects, and Control Technology of Energy Use. Environmental Protection Agency 600/7-76-002, February 1976.

7. Christianson, A.G., "Waste Heat Utilization/Reduction," In Proceedings: National Conference on Health, Environmental Effects, and Control Technology of Energy Use. Environmental Protection Agency 600/7-76-002, February 1976.

8. Resource Planning Associates, Inc., Cambridge, Massachusetts.

30<

OMIT —

# THE ROLE OF MODELING IN THE ASSESSMENT OF THERMAL POWER PLANT COOLING SYSTEM EFFECTS ON AQUATIC ENVIRONMENTS*

Robert A. Goldstein, John Maulbetsch, and Ronald Wyzga
Electric Power Research Institute
Palo Alto, California 94303

There is an urgent need to develop methodologies to assess the impact of thermal power plant cooling systems on aquatic environments. There exists a hierarchy of cooling system effects. The most simple effects to either quantify or predict are physical-chemical changes in the environment. More complex are ecological changes; while the most complex are social changes. Whatever form the needed assessment methodologies eventually take, it is obvious that models will be essential components.

The state of the modeling art for the different hierarchical levels of effects varies dramatically. Mathematical models of physical-chemical processes are most advanced, while those for social processes are least. This paper will compare the states of the art and describe how the role of modeling in the development of electric power production will change as the state of the art advances. At present, environmental analysis has not reached the point when models can be used to predict effects. The best strategy for planning power plants that will not produce unacceptable environmental impacts is to quantify the impacts of existing plants and identify basic situations that result in no significant impact, then replicate these basic situations when planning new plants. Models will play an important role in this process by providing a logical framework to identify potentially important effects and key factors to quantify.

For the long term, an ecosystem management approach is needed to guide electric power development. The short term approach to environmental assessment allows one to plan a power plant with acceptable environmental impact, but it does not provide a framework for optimization of the planning process; i.e.

the ability to develop, for a given water body, a plan to build a number of plants to obtain maximum electric power production while not exceeding the maximum acceptable environmental impact. Successful ecosystem management will require the implementation of predictive models.

/lc
1/24/77

* The contents of this document are the responsibility of the authors, and should not be attributed to EPRI.

I-15

OMIT

# PHYSICAL IMPACT OF WASTE HEAT DISPOSAL

Subrata Sengupta and Samuel S. Lee
University of Miami
Coral Gables, Florida U.S.A.

## ABSTRACT

The rising demand for electric power has resulted in the possibility that, by 1980, 5GW (5000MW) power plants may be a reality. These energy parks may cause physical disturbances in the environment significantly more concentrated than those of present day power plants. The consequent chemical and biological impacts on the ecosystem is beyond the scope of this review. While the energy balance of the atmosphere is not expected to be seriously affected, local imbalances can cause weather modifications. This paper summarizes the techniques of heat disposal available and the physical impact associated with each method. Both closed and open cycle systems are considered together with mixed systems. The heat transfer link from power plant to hydrosphere, atmosphere and finally space, is analyzed. The physical effects in the aquatic system as well as the atmosphere is documented.

Predictive techniques which are imperative for proper site selection decisions are reviewed. The models for near and far-field analysis of thermal discharges into aquatic systems are examined. The state-of-the-art in plume modelling is presented. The relative merits of phenomenological, integral and numerical models are highlighted. The effects on the atmosphere and associated predictive techniques are summarized.

The need for remote sensing, both for monitoring and model verification, has been widely accepted. Thermal scanner data has been used by many investigators including the present authors. The interesting possibility of using LANDSAT-C and SEASAT data for environmental remote sensing is documented.

Research directions in modelling are presented with emphasis on:

1) Surface heat transfer conditions
2) Turbulent closures
3) Thermocline models
4) Numerical modelling of multiport diffusers
5) Atmospheric models
6) Cooling tower plumes
7) Numerical techniques

8) Verification efforts

The expected important role of remote sensing efforts and needed research in data interpretation and resolution is established.

# THE ANSWER IS BIOLOGICAL

D. Dunlop
Florida Power and Light
Miami, Florida

# SESSION II-A
## STANDARDS

2-45-4

II-A-3

# AN APPROACH TO THERMAL WATER QUALITY STANDARDS

C.R. Jeter, P.E.
South Carolina Department of Health and Environmental Control
Columbia, South Carolina U.S.A.

## ABSTRACT

The background development and practical application for thermal water quality standards will be presented. This will include the legal framework together with the legal and administrative procedures required to develop State thermal water quality standards. Additionally, emphasis will be placed on the definition of mixing zones which is critical to the actual application of thermal standards regardless of numerical temperature limitations. Included in this definition will be a philosophical discussion of the mixing zone concept. Then, technical decisions and monitoring considerations for thermal standards will be developed. A discussion will be given on how legal variances such as Section 316(a) of the Federal Water Pollution Control Act of 1972 (PL 92-500) apply to thermal standards. Finally, the concepts of cooling ponds, cooling lakes, and multipurpose reservoirs will be discussed in conjunction with thermal standards.

## INTRODUCTION

Water quality standards have developed over the years as the major strategic tool for water quality management and control. Standards contain four major elements. These include: the use (water supply, recreation, fish, shellfish, and wildlife propagation) to be made of the water; criteria or specific quantative or qualitative limits; implementation and enforcement plans; and an antidegradation statement to protect existing high quality waters.

Thermal water quality standards, or any standards, must include at least the following considerations: (1) Protect water quality to a degree consistent with stream classifications and use. (2) Practical and enforceable to include considerations of available analytical techniques and instrumentation to determine compliance. (3) Economic and social impact of the standards in relationship to environmental damage to be alleviated.

## MIXING ZONE AND TEMPERATURE LIMITS

The most important and basic considerations to thermal water quality

37<

standards is the concept of the "mixing zone". In approaching thermal standards, the philosophy of defining the mixing zone and the physical boundary of the zone becomes at least as important and sometimes more important than any numerical temperature criteria. Further, one defined mixing zone can be more or less restrictive than what is necessary to assure the protection of a balanced indigenous population. The use of arbitrary criteria to define a mixing zone in general is not always indicative of the problems faced at a particular site. In developing the definition of the mixing zone and subsequent temperature limits for thermal standards, our philosophy was to define a relatively small area where at times there could be relatively large temperature changes. Within this zone we would expect to detect adverse ecological impact on certain occasions. However, this zone would be relatively easily monitored and would be consistent with a balanced indigenous aquatic population in the waters outside the boundary. The mixing zone definition and corresponding temperature standards for streams and lakes are as follows:

> Mixing Zone - shall mean a designated area within which specified water quality standards are not applicable. The boundary of this zone shall be determined on an individual project basis after consideration of the waste discharge and the receiving waters. A mixing zone shall not prevent free passage of fish and shall not interfere with the designated use outside its established boundary.
>
> Temperature Standards - a. All fresh waters of the State, other than those classed as AA - Trout or lakes and reservoirs, shall not exceed a maximum temperature of 32.2°C (90°F) at any time nor shall a maximum temperature rise above natural temperatures exceed 2.8°C(5°F) as a result of the discharge of heated liquids unless an appropriate temperature criteria or mixing zone, as provided below, has been established.
>
> The water temperature at the inside boundary of the mixing zone shall not be more than 10°C(18°F) greater than that of water unaffected by the heated discharge. The appropriate temperature criteria or the size of the mixing zone will be determined on an individual project basis and will be based on biological, chemical, engineering and physical considerations. Any such determination shall assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on a body of water to which the heated discharge is made and shall allow passage of aquatic organisms.

b. All waters of lakes and reservoirs of the State shall not exceed a weekly average temperature of 32.2°C(90°F) after adequate mixing of heated and normal waters as a result of heated liquids, nor shall a weekly average temperature rise above natural temperatures exceed 2.8°C(5°F) as a result of the discharge of heated liquids unless an appropriate temperature criteria or mixing zone, as provided below, has been established.

The water temperature at the inside boundary of the mixing zone shall not be more than 10°C(18°F) greater than that of water unaffected by the heated discharge. The appropriate temperature criteria or the size of the mixing zone will be determined on an individual project basis and will be based on biological, chemical, engineering and physical considerations. Any such determination shall assure the protection and propagation of a balanced, indigenous population of shellfish, fish and wildlife in and on a body of water to which the heated discharge is made and shall allow passage of aquatic organisms.

## UNIQUE AREAS

The unique nature of temperature standards and temperature as a pollutant have led to the situation where most standards include special considerations for many special type waters. These include the following:

(1) For those waters specifically classified as trout streams, the temperature should not be raised above the natural conditions.

(2) The unique nature of tidal salt water led to the following standards: The temperature of tidal salt waters shall not exceed a weekly average temperature of 2.2°C(4°F) outside a mixing zone above the natural temperature during the fall, winter or spring and shall not exceed a weekly average temperature of .8°C(1.5°F) outside a mixing zone above the natural temperature during the summer months. The size of the mixing zone will be determined on an individual project basis and will be based on biological, chemical, engineering and physical considerations. Any such determination shall assure the protection and propagation of a balanced, indigenous population of shellfish, fish and wildlife in and on a body of water to which a heated discharge is made.

## VARIANCES

The variance provision of Section 316(a) of the Federal Water Pollution Control Act of 1972 (PL 92-500) has led to other unique aspects of temperature standards. As originally conceived, this Section was an exemption from the treatment technology requirements of this Act. This has been expanded to include a modification of temperature standards. The basic proof that an applicant must submit is that the thermal discharge and subsequent temperature in the receiving water will result in a balanced indigenous population of fish, shellfish, and wildlife. In particular consideration of the 316(a) determination, the standards include a provision that all temperature limits will be subject to modifications as specified under State/Federal laws, rules, and regulations. In effect, this means that a satisfactory 316(a) determination would result in a mixing zone and temperature criteria specific to that location.

In consideration of a future policy on cooling lakes and ponds, the standards would exempt certain cooling water bodies with a primary purpose of providing a source and/or receptor or industrial cooling water which are in accordance with State/Federal laws, rules, and regulations.

## APPLICATION

The practical application of this standard approach results in a case-by-case analysis of temperature limits and mixing zone size. Special considerations are given to the protection of sensitive trout waters and salt water estuary systems. Variances would be given to cooling ponds or cooling lakes that are consistent with State/Federal guidelines.

In most cases, a specific project would do a water quality analysis or a Section 316(a) determination and the effluent limits and subsequent temperature standards and mixing zone size would be established based on this site specific study and analysis. Emphasis would be placed on the biological, chemical, engineering, and physical aspects of a project keeping in mind that the thermal discharge must be consistent with the designated use of the water body and must allow for the protection and propagation of a balanced indigenous population of shellfish, fish, and wildlife in and on the water body.

3-45-24

II-A-7

# PROPOSED ANSI GUIDE FOR AQUATIC ECOLOGICAL SURVEYS AT THERMAL POWER PLANTS

R. M. Hartman
Envirosphere Company
Norcross, Georgia U.S.A.

## ABSTRACT

This paper describes a proposed guide for aquatic ecological surveys at thermal power plants developed by the American Nuclear Subcommittees (ANS) 18.4 and 18.5, of which the author is co-chairman. It is intended that this guide, if approved after review by the American National Standard Institute (ANSI) Committee 19, will become an official industrial standard on aquatic ecological surveys.

The guide presents six principles that are important considerations when initially designing aquatic ecological surveys. The guide then develops a rationale for aquatic survey design relating to power plant development activities and the timing of ecological information needs. It also explains an ecological matrix approach for considering biotic parameters relative to major organism groups, habitat types, and cooling water system designs. The biotic parameters consider information regarding important species, abundance, spatial organism distribution, significant preexisting stresses, and certain water quality parameters.

## 1. INTRODUCTION

In licensing power plants, aquatic ecology seems to have generated more confusion regarding the extent of information required than almost any other area. There are many reasons for this, but in the view of ANS subcommittees 18.4 and 18.5, one main reason is the lack of any consistent, overall rationale. In measuring the health of an aquatic habitat and determining whether it is likely to get "sick" should a power plant be placed nearby, we are without any uniform examination method. In examining and diagnosing human illnesses, physicians have a wide range of examination techniques that they can utilize. Nevertheless, these techniques follow a general pattern of information gathering such as case histories, clinical examinations, laboratory tests, etc., that help supply basic information to determine how one person compares to what physicians have come to expect for a healthy individual. Also while physicians commonly perform certain standard tests, they vary these depending on the patient's complaint and what physical condition he appears to be in.

>1<

In aquatic ecology we appear to be without any similar physical examination routine. The rationale for why an investigator should gather data seems sometimes to be missing or confused. This is due not so much to the biological investigator but probably more so to the utility and plant design engineers, and regulatory agency officials. If a particular power plant site is the patient in our analogy, then it's as if he has walked in the physicians office with three different people, all giving the doctor different reasons and accounts for his condition and treatment.

The purpose of the ANS aquatic ecology guide is, therefore, to help develop more understanding on the part of all interested parties and more consistency in approach when designing aquatic ecological surveys for thermal electric power plants. The guide should not be a substitute for professional judgment on a site specific basis. The fact that a general routine of data gathering has been laid out doesn't mean that a professional biologist is not needed to figure out the best way to apply it and to analyze the results.

The guide is also intended to help plant design engineers and utility officials better understand and appreciate the role that aquatic ecological data should have in helping make decisions on plant design alternatives and in perfecting particular aspects of chosen designs.

The guide begins by reviewing certain basic philosophical points about aquatic ecological surveys. It then presents and explains various factors that go into the development of information matrices. Finally the matrices themselves are presented. An appendix to the guide provides a short summary of relevant federal laws and regulations. Since laws and regulations change with time, this appendix should not be considered definative or complete, especially regarding state requirements.

## 2. BACKGROUND INFORMATION

In determining aquatic ecological survey requirements at a specific power plant site, investigators should be cognizant of the mandates of appliable laws and regulations before finalizing their survey needs. Where regulations provide only very general guidance, this aquatic guide may be useful to follow to provide the added scope and detail of information needs. As a document produced by a wide range of professionals in industry and government, it gives a general consenus of what data should be provided. From this standpoint, regulatory agencies should eventually give appropriate recognition to the guide.

The guide starts out by presenting six basic principles for consideration when initially designing aquatic ecological surveys (The term "aquatic" includes freshwater, estuarine and marine environments). The first principle is the recognition of limitations inherent in the current biological state of the art. Aquatic ecology is not generally a predictive science, and often presents difficult data analysis and identification of power plant induced impacts, due to the effects of natural variables in the field. Surveys should be designed on the basis of what can be accomplished with current sampling methods and statistical analyses in differentiating plant-induced aquatic changes from other man-made and natural changes.

A second principle is the need to coordinate aquatic studies with specific schedules for siting, construction and operation of thermal power plants. This includes obtaining aquatic ecological information to help make decisions appropriate to the stage of project development. Information out of sequence is often of little value. For environmental assessment to be meaningful to reduce impacts, there must be feedback to design engineering so that design costs can be weighed against potential environmental costs.

A third principle is development of aquatic ecological information based on impacts that are credible for a specific plant and site combination. Broad, general survey information, may be useful for site selection, but beyond that stage is wasteful of time and money. Assessment of effects of power plants on aquatic ecological systems requires carefully planned and narrowly focused impact detecting surveys. Critical survey designs, which address specific problems relating to the plant and site situations, usually achieve the objectives of regulatory agencies while protecting the utilities plant design and economic interests.

A closely related fourth principle concerns sequencing surveys to look for organisms that are first impacted. Some regulatory agencies request ecological information for essentially all trophic levels. While an impact at one level may have an influence throughout the ecosystem, it is more effective in the practical world of power plant planning to concentrate surveys on biota to be first affected by plant operation and construction. These so called "indicator organisms", commonly have a delicate chemical-physical balance. By focusing on these indicator organisms first, surveys need to be expanded to other trophic levels only if unacceptable impacts on indicator organisms are detected.

A fifth principle is incorporation of accepted biometric techniques in the design of surveys so that power plant-induced impacts can be distinguished, to the extent possible with reasonable effort, from natural stresses and variability. Lack of controls often prevents use of the experimental approach to the assessment of impacts in the field. Data obtained from sampling can only yield estimates of population size and survival rates. Impact evaluation must rely chiefly on approximate evaluation methods that are based largely on observational studies.

A sixth principle is recognition of the value of uniformity in design, conduct and analysis of aquatic ecological surveys. The advantage in working towards uniformity is twofold. First, it will make the license review process more efficient, and second, it will allow comparison of data from one site to another. This comparison could aid in detecting ecological trends in a region, lead to better estimates of plant-induced impacts, and ultimately result in more efficient design of environmental surveys for future thermal power plants. Due to the uniqueness of each site and plant combination, complete uniformity of surveys is not achievable. Nevertheless, the authors hope that by a reasonable and flexible following of the information outline in the guide, the desirable degree of survey uniformity can begin to be achieved.

## 3. SURVEY COMPONENTS

### 3.1 Introduction

As an aid to planning and organizing the resultant ecological information, the authors adopted a matrix approach to the development of the surveys. Matrices present the major elements of ecological surveys (i.e., timing and extent of investigations, habitat types and organism groups, cooling system design alternatives, quality and frequency of informational needs, and specific biotic parameters.) Each matrix provides an overview of the entire aquatic ecological survey effort from initial site evaluation to operational monitoring for a major type of habitat.

In differentiating the aquatic ecological information for specific plant sites, there are five major survey components addressed in the guide. The first is the rationale for the division of survey phases and stages relative to power plant development activities and timing of ecological information needs. The second is the major power plant cooling water system designs and their relationship to ecological information needs. Thirdly, major organism groupings for which ecological information may be required at different survey stages is discussed. The fourth component concerns the major aquatic habitat types and how the relative ecological importance of the different organism groups can vary. The last matrix component is the identification of biotic parameters for the various surveys.

### 3.2 Stages

#### Administrative and Engineering Milestone Schedules

Under present conditions (March, 1977) about 9-10 years are needed to plan for and construct a nuclear power plant. Similar requirements, though a shorter 7-8 year schedule, are necessary for coal fired power plants.

Figure 1 illustrates a typical development schedule for a nuclear power plant, and indicates how certain major aquatic survey stages relate to various milestone project activities. Four major survey stages (Site Selection, Preconstruction, Preoperation and Operational) all relate to major project licensing, engineering or construction objectives.

## Division of Ecological Survey Stages

The four major ecological survey stages listed above need timely information to correspond with and input to administrative and engineering decisions for the plant. The purpose and further subdivision of each of the survey stages is the following:

I Site Selection Phase

1. Initial Evaluation Survey - to select sites from candidate regions.
2. Site Selection Survey - to rank candidate sites.

II Preconstruction Phase

1. Site-Plant Design Evaluation - to obtain data for preliminary engineering.
2. Baseline Survey - to obtain data for ER and impact prediction.
3. Site Exploration Monitoring - for possible significant environmental impacts.

III Preoperation Phase

1. Construction Monitoring - to monitor impacts of construction activities
2. Preoperation Survey - to provide baseline information for operation monitoring.
3. Start-up Monitoring - (optional) includes any special studies to identify significant changes in ecosystem during start-up testing.

IV Operation Phase

Determined by NRC's Environmental Technical Specifications and state required monitoring during operation.

It is not intended that simultaneously occurring survey stages maintain discreet and separate surveys. This could result in unnecessary duplication of effort. Also, please note that the survey matrices in this guide were developed to identify information needs, but not necessarily study (work) requirements. Thus, if the information is already available from other sources, no survey or field data gathering is necessary for the available information.

## 3.3 Plant Design Classifications

### General

Plant design alternatives can and should play a major role in being affected by and in turn, affecting the design of aquatic ecological surveys. Section 10 of NRC Regulatory Guide 4.2 specifies certain alternatives to be discussed in a nuclear plant's ER. Each of the following design alternatives should be considered, and, depending on their resultant technical and economic feasibility, need aquatic biological data before making final decisions:

(1) Type of cooling system and its operating parameters
(2) Intake structure
(3) Discharge structure
(4) Chemical waste treatment systems
(5) Biocide treatment method
(6) Sanitary waste system
(7) Liquid radwaste systems
(8) Dock facilities
(9) Dam design and location

Alternatives for intake and discharge structures can impact ecosystems through improper location, water velocity, configuration of traveling screens, or improper avoidance mechanisms for fish. EPA's development document (1) on intake structures and its draft 316(a) and 316(b) guidelines on protection of aquatic organisms (Section 1.2), have indicated types of impacts caused by intake and discharge structures and provided designs available for reducing them. Major aquatic impacts to be considered in design of surveys are the following:

(1) Attraction and entrapment of organisms around intake structures
(2) Impingement of aquatic biota on intake trash racks and screens
(3) Entrainment of aquatic biota through cooling system, and resultant impacts due to thermal, chemical, physical and mechanical damage
(4) Entrainment and thermal stress on aquatic biota within mixing zone
(5) Alteration of water quality in intake and discharge areas
(6) Scouring and silting of bottom habitat near intake and discharge
(7) Changes in water quality and water level due to consumptive use
(8) Changes in currents around intake and discharge structures
(9) Blockage or delay of organism movement by thermal or physical barriers
(10) Loss of habitat by structures
(11) Plant waste discharges

---

(1) Development Document for Cooling Water Intake Structures, USEPA, EPA440/174/015.

46<

From a plant design standpoint, these impacts vary in importance between open and closed cycle cooling systems. The biological survey matrices are therefore different for these alternatives. Other plant designs can likewise cause variance in some of the survey matrices. If compliance with EPA's effluent limitation guidelines is achieved, impacts from plant chemical discharges will usually be lowered to the point where no specific aquatic ecological monitoring for chemical impacts will be necessary.

### Cooling Systems

As previously mentioned, a major area of plant design affecting aquatic ecological surveys is the type of cooling-water system implemented. Examples of closed cycle systems currently used are cooling or spray augmented ponds, natural or mechanical draft wet towers, dry towers, combined wet-dry mechanical draft towers or fan-assisted natural draft wet towers. This guide groups and discusses all closed cycle cooling methods (except dry cooling towers where aquatic surveys are usually unnecessary), under the heading of "closed cycle cooling".

### 3.4 Organism Groupings

Organism groupings selected for use in the various biological matrices include the primary producers (periphyton, phytoplankton and macrophytes) and consumers (zooplankton, macro-invertebrates and fish). Groupings include all life history stages under the same organism category. Although public and regulatory agencies are most interested in protection of commercially and recreationally valuable fish and macro-inverterbrates, it can be important to study other organism groups because of their ecological relationships to the more valuable forms. For this parameter the survey matrices can only offer very general advise. Specific groupings selected for study at each site should be based on sound site specific professional judgement.

Population dynamics and biotic interrelationships help define "important species" within each grouping. A species is defined as an "important species" if a specific casual link can be identified between it and the facility, and if one or more of the following criteria applies:

(1) The species is commercially or recreationally valuable
(2) The species is threatened or endangered
(3) The species affects the well-being of some important species within criteria (1) or (2).
(4) The species is critical to the structure and function of the ecological system.

For "important species or groups", certain qualitative or quantitative studies concerning biotic parameters such as principal associations, abundance, spatial distribution of life history stages and significant existing stresses may need to be conducted so that plant-induced impacts can be estimated and separated from natural variations. These biotic parameters will be discussed in more detail in section 3.6.

### 3.5 Habitat Types

This section differentiates aquatic surveys based on the differences in habitat characteristics of ocean, estuarine, lake and river environments. The ocean habitat includes offshore and open coastal sites, and possesses a different range of species and physical-chemical parameters than the other habitats. The differences between habitats are one of the most important variables warranting modifications in the scope and detail of aquatic biological surveys. The literature abounds at describing the detailed characteristics of the four major habitat types chosen for use in the survey matrices. No attempt will be made in this paper to point out the differing characteristics of each habitat group but appreciation of these characteristics are important in understanding the rationale for each matrix.

### 3.6 Biotic Parameters

Once an investigator has identified important species or groups, then the remaining biotic information parameters should be considered as applying to important species or groups.

#### Abundance (Ab)

It is sometimes more important to know whether a population is increasing or decreasing in numbers or biomass than to have a quantitative measurement of its size. Similarly, it is often adequate to have only a relative abundance measurement of a species to establish changes. Population sizes often change very rapidly and are very difficult to measure accurately, but numbers of organisms caught per standardized unit of effort (relative abundance) may serve as a useful measure of population change.

#### Spatial Distribution (S)

The distribution of organisms in a given body of water depends upon the reproductive, migratory and other behavioral habits of specific organisms, as well as current patterns, physical-chemical parameters and substrate characteristics. Power plant facilites and operations may also influence the spatial distribution of organisms.

Identifying the spatial distribution of life history stages of important species or groups on an appropriate sampling frequency can be important for inventory purposes, for interfacing biological sensitivities with power plant design and operations and for assessing possible power plant-induced effects on aquatic populations.

48< RMH

## Significant Existing Stresses (SS)

Stress on an organism, population or ecosystem can result from any natural or man-induced change in an environment. The capacity of an organism to adjust to stress is inherited or acquired, and stress can result in physiological, morphological or behavioral changes. Stresses on or involving biota present in a body of water upon which a thermal power plant is to be located should be determined prior to construction of the plant. The existence of such stresses should be given appropriate consideration in conjunction with the siting, design, construction, operation, and assessment of impacts at a power plant.

## 4. ECOLOGICAL INFORMATION BY SURVEY STAGES

This section presents representative ecological study programs for the four major phases of thermal power plant development. Representative information requirements presented in the text and matrices (Tables 1 through 4) should be considered before any aquatic ecological studies are initiated. The objective is to provide ecological information relevant to plant siting, design, construction, and operation so that ecological aspects can be considered as engineering decisions are made. The matrices indicate the level and type of information normally needed to meet these objectives at various stages. In certain cases, as examples indicate, the matrices must be modified on a site-by-site basis. For several of the stages, blank matrices, indicating that ecological surveys are needed only when unusual circumstances are encountered, are presented.

The matrices were developed to provide guidance in design of aquatic ecological survey programs necessary to predict and monitor impacts on aquatic organisms of thermal power plant construction and operation. The intent of the matrices is to provide a general overview of major aquatic systems which may be affected by thermal power plants and indicate typical information needs for each system. In all instances, final program design is highly dependent on professional judgment with respect to plant and site specific characteristics.

In developing the examples presented in the matrices, the authors considered several factors, including ecological importance of organisms, probable impacts on organisms, probable cost effectiveness of survey programs, and probable information needs of reasonable regulatory decisions. Blank cells in the matrices imply that the indicated organisms groups are ecologically unimportant (e.g., phytoplankton in detritus based food webs), that information collection be recommended elsewhere, since in the usual case important impacts are not to be expected. Another way of stating this is that aquatic ecological information could be collected at a cost and effort commensurate with its probable value for impact analysis, plant design or regulatory decision making.

Certain survey stages were judged so site-plant specific that it was considered unnecessary to develop matrices for these. All of these survey stages are dependent on knowledge of unique site sensitivities, and plant design characteristics.

In the Site Selection Survey, preliminary estimates should be made of the particular role of each organism grouping at the site under consideration, and the identification of the "important species" in each group. This determination is usually sufficient for the site screening process. At the Baseline Survey stage, greater consideration should be given to determining "important species" and "important organism groupings". A checklist of organisms likely to be especially vulnerable to man-made stresses should be developed. Factors crucial to environmental stability and community diversity should be protected by:

(1) Safeguarding the normal flow of food and energy in the biological system
(2) Minimizing power plant-induced stress on individual organisms or species. In this regard, certain organisms are more vulnerable than others and can, therefore, be used as indicator species.
(3) Protecting major food web pathways so that stress on one significant species does not break the web and thus endanger survival of other species. In this regard, certain organisms are more vulnerable than others and can, therefore, be used as indicator species.
(4) Protecting the major food web pathways so that stress on one significant species does not break the web and thus endanger survival of other species. Environmental stress must be limited such that recovery can be attained in a relatively short time. Fluctuations should remain within natural limits of population changes, seasonal variations, and inherent physiological tolerance.

## 5. PHYSICAL, CHEMICAL, AND WATER QUALITY INFORMATION

It is customary for ecological surveys of aquatic systems to include measurements of certain physical-chemical and water quality parameters which have a direct association with the health of biota. Important parameters that influence aquatic systems which are discussed in the guide are listed below:

1. Currents, circulation patterns and flushing rates
2. Temperature
3. Sediments
4. Dissolved Oxygen
5. Turbidity and Suspended Solids
6. pH
7. Dissolved Solids 50<
8. Nutrients and Productivity

9. Salinity
10. Other Water Quality Parameters

Measurements of all parameters may not be necessary at a particular site. However, additional parameters such as the presence of industrial effluents, may need to be included if a site is in an area already receiving significant waste discharges. Table 5 gives an example of the type of physical, chemical, and water quality information needs that might be required for ecological predictions and assessments at a particular site. This table is not intended to indicate water quality parameters needed for other purposes.

## CONCLUSION

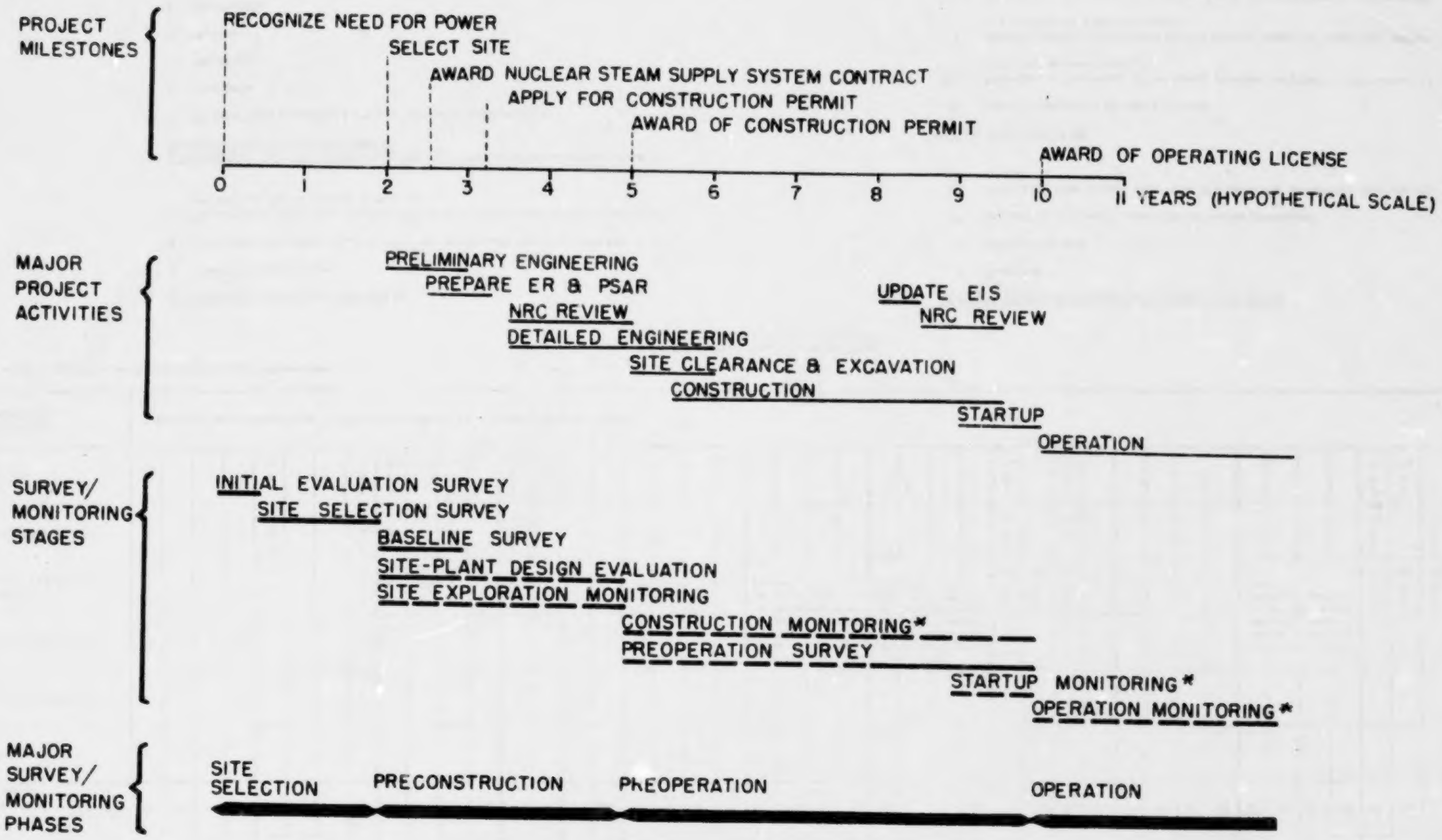
Greater understanding and consistency of aquatic ecological information gathering for thermal power plants is needed. An ad hoc American Nuclear Society Subcommittee of industrial and governmental professionals has developed a general aquatic guide for this purpose. This guide will be submitted to ANSI for adoption as an official industrial standard.

The current state of confusion on what aquatic ecology information is necessary for plant designers and regulatory officials needs to be corrected. The major NEPA regulatory agency for fossil plants, the Corps of Engineers, has no guidelines for what aquatic data is needed for fossil power plant permit actions. The Nuclear Regulatory Commissions Regulatory Guide 4.2 for nuclear plants, have been criticized by some as not being clear and specific enough. On the other hand, EPA's draft 316(a) and 316(b) guidance manuals have been considered by many industrial officials to impose excessive and extensive aquatic surveys out of proportion to credible impact problems. While industry representatives may argue about one agencies excessiveness or anothers absence of guides, they must realize that aquatic biological data are not always accorded the proper attention in industries choice, location, or designs of thermal power plants. Gone are the days when aquatic data was needed only as "filler" information for environmental reports. Now it should be accepted that certain aquatic data is needed to feed into decision making of site location, cooling water design alternatives, and operating conditions. This information must also be given proper weight in accordance with its impact avoidance potential and the cost of design compliance.

It is hoped that this aquatic guide provides a means for outlining what biological information needs to be collected and when and for what purpose it is needed. We are not faced with an academic research situation in evaluating aquatic power plant impacts. Decisions must be made on a timely basis if we are to have adequate supplies of electricity. This guide should provide an outline of the aquatic data needs for timely decision making.

References

1. United States Environmental Protection Agency, Development Document for Cooling Water Intake Structures, EPA440/174/015


PROJECT MILESTONES
RECOGNIZE NEED FOR POWER
SELECT SITE
AWARD NUCLEAR STEAM SUPPLY SYSTEM CONTRACT
APPLY FOR CONSTRUCTION PERMIT
AWARD OF CONSTRUCTION PERMIT
AWARD OF OPERATING LICENSE
0
1
2
3
4
5
6
7
8
9
10
11 YEARS (HYPOTHETICAL SCALE)
MAJOR PROJECT ACTIVITIES
PRELIMINARY ENGINEERING
PREPARE ER & PSAR
NRC REVIEW
DETAILED ENGINEERING
SITE CLEARANCE & EXCAVATION
CONSTRUCTION
UPDATE EIS
NRC REVIEW
STARTUP
OPERATION
SURVEY/ MONITORING STAGES
INITIAL EVALUATION SURVEY
SITE SELECTION SURVEY
BASELINE SURVEY
SITE-PLANT DESIGN EVALUATION
SITE EXPLORATION MONITORING
CONSTRUCTION MONITORING*
PREOPERATION SURVEY
STARTUP MONITORING*
OPERATION MONITORING*
MAJOR SURVEY/ MONITORING PHASES
SITE SELECTION
PRECONSTRUCTION
PREOPERATION
OPERATION

*MAY CONTINUE BEYOND THIS TIME AS APPROPRIATE

Fig. 1 Typical development schedule for nuclear power plants in the United States.

TABLE 1. REPRESENTATIVE ECOLOGICAL MATRIX FOR OCEAN HABITAT.*

| MAJOR PHASE | SITE SELECTION | | | | | | | | PRECONSTRUCTION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | INITIAL EVALUATION SURVEY | | | | SITE SELECTION SURVEY | | | | BASELINE SURVEY | | | | | | | |
| COOLING SYSTEM CLASSIFICATION | OPEN & CLOSED | | | | OPEN & CLOSED | | | | OPEN | | | | CLOSED | | | |
| ORGANISM GROUP / BIOTIC PARAM | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | | | | | | | | | | | | | | | | |
| PHYTOPLANKTON | | | | 1<br>A<br>I | | | | | | | | | | | | |
| ZOOPLANKTON | 1<br>A<br>I | | | 1<br>A<br>I | | | | | 2<br>C<br>III | | | | | | | |
| MACRO-INVERTEBRATES | 1<br>A<br>I | | | 1<br>A<br>I | 2<br>A<br>II | | | 2<br>A<br>II | 2<br>C<br>III | 3<br>C<br>III | 3<br>C<br>III | | 2<br>B<br>III | | | |
| MACROPHYTES | 1<br>A<br>I | | | 1<br>A<br>I | 2<br>A<br>II | | | 2<br>A<br>II | 2<br>B<br>III | | 2<br>B<br>III | | 2<br>B<br>III | | | |
| FISHES | 1<br>A<br>I | | | 1<br>A<br>I | 2<br>A<br>II | | | 2<br>A<br>II | 2<br>F<br>III | | 2<br>F<br>III | | 2<br>B<br>III | 1<br>A<br>II | | |
| PHYSICAL-CHEMICAL | Refer to appropriate stage of Physical Chemical Water Quality Matrix, Table 5. | | | | | | | | | | | | | | | |

| MAJOR PHASE | PRECONSTRUCTION | | | | | | | | PREOPERATION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | SITE-PLANT DESIGN EVALUATION | | | | SITE EXPLORATION MONITORING | | | | CONSTRUCTION MONITORING | | | | PREOPERATION SURVEY | | | |
| COOLING SYSTEM CLASSIFICATION | OPEN & CLOSED | | | | OPEN & CLOSED | | | | OPEN & CLOSED | | | | OPEN | | | |
| ORGANISM GROUP / BIOTIC PARAM | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | | | | | | | | | | | | | | | | |
| PHYTOPLANKTON | | | | | | | | | | | | | | | | |
| ZOOPLANKTON | | | | | Only site specific studies related to potential impacts of site exploration activities are required. | | | | Only site specific studies related to potential impacts of site construction activities are required | | | | | | | |
| MACRO-INVERTEBRATES | | | | | | | | | | | | | 2<br>F<br>IV | 3<br>F<br>IV | 3<br>F<br>IV | |
| MACROPHYTES | | | | | | | | | | | | | 2<br>F<br>IV | | 2<br>F<br>IV | |
| FISHES | | | | | | | | | | | | | 2<br>F<br>IV | | 3<br>F<br>IV | |
| PHYSICAL-CHEMICAL | | | | | | | | | | | | | | | | |

| MAJOR PHASE | PREOPERATION | | | | | | | | OPERATION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | PREOPERATION SURVEY | | | | STARTUP MONITORING | | | | OPERATION MONITORING | | | | | | | |
| COOLING SYSTEM CLASSIFICATION | CLOSED | | | | OPEN & CLOSED | | | | OPEN | | | | CLOSED | | | |
| ORGANISM GROUP / BIOTIC PARAM | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | | | | | | | | | | | | | | | | |
| PHYTOPLANKTON | | | | | | | | | | | | | | | | |
| ZOOPLANKTON | | | | | Only site specific studies related to potential impacts of startup testing activities are required | | | | | | | | | | | |
| MACRO-INVERTEBRATES | | | | | | | | | 2<br>F<br>IV | 3<br>F<br>IV | 3<br>F<br>IV | | | | | |
| MACROPHYTES | | | | | | | | | 2<br>F<br>IV | | 2<br>F<br>IV | | | | | |
| FISHES | | | | | | | | | 2<br>F<br>IV | 3<br>F<br>IV | | | | | | |
| PHYSICAL-CHEMICAL | | | | | | | | | | | | | | | | |

*Use only in conjunction with text and site specific considerations.

## KEY TO CODES LISTED IN MATRIX

**SOURCE OF INFORMATION NEED**

1. From existing sources
2. Estimates from field observations if not adequately available from No. 1
3. Quantitative from field studies with level of statistical precision that would be appropriate for impact evaluation

**FREQUENCY OF INFORMATION NEED** (for duration of survey stage or duration of real or potential impact)

A. At least once by end of survey, or annually if appropriate

B. Quarterly

C. Monthly

D. Weekly

E. Continually

F. Periodically. Either frequency of sampling in keeping with identification of the parameter when it undergoes some important change, or a fixed periodic schedule

**SPATIAL DISTRIBUTION OF INFORMATION NEED**

I. Regional

II. General site area

III. Immediate site impact area (for particular parameter)

IV. Immediate site impact area (for the particular parameter) plus control area(s)

**BIOTIC PARAMETERS**

IS. Identify important species or groups

Ab. Abundance. Estimates of numbers, biomass, or relative abundance, of important species or groups

S. Identify spatial distribution of life history stages of important species or groups at indicated frequency

SS. Identify significant existing stresses on or involving important species or groups

TABLE 2. REPRESENTATIVE ECOLOGICAL MATRIX FOR ESTUARY HABITAT.*

| MAJOR PHASE | SITE SELECTION | | | | | | | | PRECONSTRUCTION | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | INITIAL EVALUATION SURVEY | | | | SITE SELECTION SURVEY | | | | BASELINE SURVEY | | | | | | | | SITE-PLANT DESIGN EVALUATION | | | |
| COOLING SYSTEM CLASSIFICATION | OPEN & CLOSED | | | | OPEN & CLOSED | | | | OPEN | | | | CLOSED | | | | OPEN & CLOSED | | | |
| BIOTIC PARAM / ORGANISM GROUP | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | | | | | | | | | 2<br>B<br>III | 3<br>B<br>III | | | | | | | | | | |
| PHYTOPLANKTON | 1<br>A<br>I | | | 1<br>A<br>I | | | | | 2<br>F<br>III | 3<br>F<br>III | | | 2<br>B<br>III | | | | | | | |
| ZOOPLANKTON | 1<br>A<br>I | | | 1<br>A<br>I | | | | | 2<br>C<br>III | 3<br>C<br>III | | | 2<br>B<br>III | | | | | | | |
| MACRO INVERTEBRATES | 1<br>A<br>I | | | 1<br>A<br>I | 2<br>A<br>II | | | 2<br>A<br>II | 2<br>C<br>III | 3<br>C<br>III | 3<br>C<br>III | | 2<br>B<br>III | 2<br>B<br>III | | | | | | |
| MACROPHYTES | 1<br>A<br>I | | | 1<br>A<br>I | 2<br>A<br>II | | | 2<br>A<br>II | 2<br>B<br>III | | 2<br>B<br>III | | 2<br>B<br>III | | | | | | | |
| FISHES | 1<br>A<br>I | | | 1<br>A<br>I | 2<br>A<br>II | | | 2<br>A<br>II | 2<br>F<br>III | | 2<br>F<br>III | | 2<br>B<br>III | 1<br>A<br>II | | | | | | |
| PHYSICAL-CHEMICAL | Refer to appropriate stage of Physical Chemical Water Quality Matrix, Table 5. | | | | | | | | | | | | | | | | | | | |

| MAJOR PHASE | PRECONSTRUCTION | | | | PREOPERATION | | | | | | | | | | | | | | | | OPERATION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | SITE EXPLORATION MONITORING | | | | CONSTRUCTION MONITORING | | | | PREOPERATION SURVEY | | | | | | | | STARTUP MONITORING | | | | OPERATION MONITORING | | | | | | | |
| COOLING SYSTEM CLASSIFICATION | OPEN & CLOSED | | | | OPEN & CLOSED | | | | OPEN | | | | CLOSED | | | | OPEN & CLOSED | | | | OPEN | | | | CLOSED | | | |
| BIOTIC PARAM / ORGANISM GROUP | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| PHYTOPLANKTON | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ZOOPLANKTON | Only site specific studies related to potential impacts of site exploration activities are required. | | | | Only site specific studies related to potential impacts of site construction activities are required | | | | | | | | | | | | Only site specific studies related to potential impacts of startup testing activities are required | | | | | | | | | | | |
| MACRO INVERTEBRATES | | | | | | | | | 2<br>F<br>IV | 3<br>F<br>IV | 3<br>F<br>IV | | 2<br>F<br>IV | 3<br>F<br>IV | | | | | | | 2<br>F<br>IV | 3<br>F<br>IV | 3<br>F<br>IV | | 2<br>F<br>IV | 3<br>F<br>IV | | |
| MACROPHYTES | | | | | | | | | 2<br>F<br>IV | | 2<br>F<br>IV | | | | | | | | | | 2<br>F<br>IV | | 2<br>F<br>IV | | | | | |
| FISHES | | | | | | | | | 2<br>F<br>IV | 3<br>F<br>IV | 2<br>F<br>IV | | 2<br>F<br>IV | 3<br>F<br>IV | | | | | | | 2<br>F<br>IV | 3<br>F<br>IV | 2<br>F<br>IV | | 2<br>F<br>IV | 3<br>F<br>IV | | |
| PHYSICAL-CHEMICAL | Refer to appropriate stage of Physical Chemical Water Quality Matrix, Table 5. | | | | | | | | | | | | | | | | | | | | | | | | | | | |

*Use only in conjunction with text and site specific considerations.

KEY TO CODES LISTED IN MATRIX

SOURCE OF INFORMATION NEED

1 From existing sources

2 Estimates from field observations if not adequately available from No. 1

3 Quantitative from field studies with level of statistical precision that would be appropriate for impact evaluation

FREQUENCY OF INFORMATION NEED (for duration of survey stage or duration of real or potential impact)

A. At least once by end of survey, or annually if appropriate

B. Quarterly

C. Monthly

D. Weekly

E. Continually

F. Periodically. Either frequency of sampling in keeping with identification of the parameter when it undergoes some important change, or a fixed periodic schedule

SPATIAL DISTRIBUTION OF INFORMATION NEED

I. Regional

II. General site area

III. Immediate site impact area (for particular parameter)

IV. Immediate site impact area (for the particular parameter) plus control area(s)

BIOTIC PARAMETERS

IS. Identify important species or groups

Ab. Abundance. Estimates of numbers, biomass, or relative abundance, of important species or groups

S. Identify spatial distribution of life history stages of important species or groups at indicated frequency

SS. Identify significant existing stresses on or involving important species or groups

TABLE 3. REPRESENTATIVE ECOLOGICAL MATRIX FOR LAKE HABITAT.*

| MAJOR PHASE | SITE SELECTION | | | | | | | | PRECONSTRUCTION | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | INITIAL EVALUATION SURVEY | | | | SITE SELECTION SURVEY | | | | BASELINE SURVEY | | | | | | | | SITE PLANT DESIGN EVALUATION | | | | SITE EXPLORATION MONITORING | | | |
| COOLING SYSTEM CLASSIFICATION | OPEN & CLOSED | | | | OPEN & CLOSED | | | | OPEN | | | | CLOSED | | | | OPEN & CLOSED | | | | OPEN & CLOSED | | | |
| ORGANISM GROUP / BIOTIC PARAM | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | | | | | | | | | 2<br>B<br>III | 3<br>B<br>III | | | | | | | | | | | | | | |
| PHYTOPLANKTON | 1<br>A<br>I | | | 1<br>A<br>I | | | | | 2<br>F<br>III | 3<br>F<br>III | | | 2<br>B<br>III | | | | | | | | | | | |
| ZOOPLANKTON | 1<br>A<br>I | | | 1<br>A<br>I | | | | | 2<br>F<br>III | 3<br>F<br>III | | | 2<br>B<br>III | | | | | | | | Only site specific studies related to potential impacts of site exploration activities are required | | | |
| MACRO INVERTEBRATES | 1<br>A<br>I | | | 1<br>A<br>I | 2<br>A<br>II | | | 2<br>A<br>II | 2<br>C<br>III | 3<br>C<br>III | 3<br>C<br>III | | 2<br>B<br>III | 2<br>B<br>III | | | | | | | | | | |
| MACROPHYTES | 1<br>A<br>I | | | 1<br>A<br>I | 2<br>A<br>II | | | 2<br>A<br>II | 2<br>B<br>III | | 2<br>B<br>III | | 2<br>B<br>III | | | | | | | | | | | |
| FISHES | 1<br>A<br>I | | | 1<br>A<br>I | 2<br>A<br>II | | | 2<br>A<br>II | 2<br>F<br>III | | 2<br>F<br>III | | 2<br>B<br>III | 1<br>A<br>II | | | | | | | | | | |
| PHYSICAL CHEMICAL | Refer to appropriate stage of Physical Chemical Water Quality Matrix, Table 5. | | | | | | | | | | | | | | | | | | | | | | | |

| MAJOR PHASE | PREOPERATION | | | | | | | | | | | | | | | | OPERATION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | CONSTRUCTION MONITORING | | | | PREOPERATION SURVEY | | | | | | | | STARTUP MONITORING | | | | OPERATION MONITORING | | | | | | | |
| COOLING SYSTEM CLASSIFICATION | OPEN & CLOSED | | | | OPEN | | | | CLOSED | | | | OPEN & CLOSED | | | | OPEN | | | | CLOSED | | | |
| ORGANISM GROUP / BIOTIC PARAM | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | | | | | | | | | | | | | | | | | | | | | | | | |
| PHYTOPLANKTON | | | | | | | | | | | | | | | | | | | | | | | | |
| ZOOPLANKTON | Only site specific studies related to potential impacts of site construction activities are required | | | | | | | | | | | | Only site specific studies related to potential impacts of startup testing activities are required | | | | | | | | | | | |
| MACRO INVERTEBRATES | | | | | 2<br>F<br>IV | 3<br>F<br>IV | 3<br>F<br>IV | | 2<br>F<br>IV | | | | | | | | 2<br>F<br>IV | 3<br>F<br>IV | 3<br>F<br>IV | | 2<br>F<br>IV | | | |
| MACROPHYTES | | | | | 2<br>F<br>IV | | 2<br>F<br>IV | | | | | | | | | | 2<br>F<br>IV | | 2<br>F<br>IV | | | | | |
| FISHES | | | | | 2<br>F<br>IV | 3<br>F<br>IV | 2<br>F<br>IV | | 2<br>F<br>IV | | | | | | | | 2<br>F<br>IV | 3<br>F<br>IV | 2<br>F<br>IV | | 2<br>F<br>IV | | | |
| PHYSICAL CHEMICAL | | | | | | | | | | | | | | | | | | | | | | | | |

*Use only in conjunction with text and site specific considerations

KEY TO CODES LISTED IN MATRIX

SOURCE OF INFORMATION NEED

1 From existing sources

2 Estimates from field observations if not adequately available from No. 1

3 Quantitative from field studies with level of statistical precision that would be appropriate for impact evaluation

FREQUENCY OF INFORMATION NEED (for duration of survey stage or duration of real or potential impact)

A At least once by end of survey, or annually if appropriate

B Quarterly

C Monthly

D Weekly

E Continually

F Periodically. Either frequency of sampling in keeping with identification of the parameter when it undergoes some important change, or a fixed periodic schedule

SPATIAL DISTRIBUTION OF INFORMATION NEED

I. Regional

II. General site area

III. Immediate site impact area (for particular parameter)

IV. Immediate site impact area (for the particular parameter) plus control area(s)

BIOTIC PARAMETERS

IS Identify important species or groups

Ab Abundance. Estimates of numbers, biomass, or relative abundance, of important species or groups

S Identify spatial distribution of life history stages of important species or groups at indicated frequency

SS Identify significant existing stresses on or involving important species or groups

TABLE 4. REPRESENTATIVE ECOLOGICAL MATRIX FOR RIVER HABITAT*

| MAJOR PHASE | SITE SELECTION | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | INITIAL EVALUATION SURVEY | | | | SITE SELECTION SURVEY | | | |
| COOLING SYSTEM CLASSIFICATION | OPEN & CLOSED | | | | OPEN & CLOSED | | | |
| ORGANISM GROUP / BIOTIC PARAM | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | | | | | | | | |
| PHYTOPLANKTON | 1 A I | | | 1 A I | | | | |
| ZOOPLANKTON | 1 A I | | | 1 A I | | | | |
| MACRO-INVERTEBRATES | 1 A I | | | 1 A I | 2 A II | | | 2 A II |
| MACROPHYTES | 1 A I | | | 1 A I | 2 A II | | | 2 A II |
| FISHES | 1 A I | | | 1 A I | 2 A II | | | 2 A II |
| PHYSICAL-CHEMICAL | Refer to appropriate stage of Physical Chemical Water Quality Matrix, Table 5. | | | | | | | |

| MAJOR PHASE | PRECONSTRUCTION | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | BASELINE SURVEY | | | | | | | | SITE PLANT DESIGN EVALUATION | | | | SITE EXPLORATION MONITORING | | | |
| COOLING SYSTEM CLASSIFICATION | OPEN | | | | CLOSED | | | | OPEN & CLOSED | | | | OPEN & CLOSED | | | |
| ORGANISM GROUP / BIOTIC PARAM | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | 2 B III | 3 B III | | | 2 B III | 2 B III | | | | | | | | | | |
| PHYTOPLANKTON | 2 F III | 3 F III | | | 2 B III | | | | | | | | | | | |
| ZOOPLANKTON | 2 F III | 3 F III | | | 2 B III | | | | | | | | Only site specific studies related to potential impacts of site exploration activities are required | | | |
| MACRO-INVERTEBRATES | 2 C III | 3 C III | 3 C III | | 2 B III | 2 B III | | | | | | | | | | |
| MACROPHYTES | 2 B III | | 2 B III | | 2 B III | | | | | | | | | | | |
| FISHES | 2 F III | | 2 F III | | 2 B III | 1 A II | | | | | | | | | | |
| PHYSICAL-CHEMICAL | | | | | | | | | | | | | | | | |

| MAJOR PHASE | PREOPERATION | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | CONSTRUCTION MONITORING | | | | PREOPERATION SURVEY | | | | | | | | STARTUP MONITORING | | | |
| COOLING SYSTEM CLASSIFICATION | OPEN & CLOSED | | | | OPEN | | | | CLOSED | | | | OPEN & CLOSED | | | |
| ORGANISM GROUP / BIOTIC PARAM | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | | | | | | | | | | | | | | | | |
| PHYTOPLANKTON | | | | | | | | | | | | | | | | |
| ZOOPLANKTON | Only site specific studies related to potential impacts of site construction activities are required | | | | | | | | | | | | Only site specific studies related to potential impacts of startup testing activities are required | | | |
| MACRO-INVERTEBRATES | | | | | 2 F IV | 3 F IV | 3 F IV | | 2 F IV | | | | | | | |
| MACROPHYTES | | | | | | | | | | | | | | | | |
| FISHES | | | | | 2 F IV | 3 F IV | 2 F IV | | 2 F IV | | | | | | | |
| PHYSICAL-CHEMICAL | | | | | | | | | | | | | | | | |

| MAJOR PHASE | OPERATION | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SURVEY MONITORING STAGE | OPERATION MONITORING | | | | | | | |
| COOLING SYSTEM CLASSIFICATION | OPEN | | | | CLOSED | | | |
| ORGANISM GROUP / BIOTIC PARAM | IS | Ab | S | SS | IS | Ab | S | SS |
| PERIPHYTON | | | | | | | | |
| PHYTOPLANKTON | | | | | | | | |
| ZOOPLANKTON | | | | | | | | |
| MACRO-INVERTEBRATES | 2 F IV | 3 F IV | 3 F IV | | 2 F IV | | | |
| MACROPHYTES | | | | | | | | |
| FISHES | 2 F IV | 3 F IV | 2 F IV | | 2 F IV | | | |
| PHYSICAL-CHEMICAL | | | | | | | | |

*Use only in conjunction with text and site specific considerations

## KEY TO CODES LISTED IN MATRIX

### SOURCE OF INFORMATION NEED

1. From existing sources
2. Estimates from field observations if not adequately available from No. 1
3. Quantitative from field studies with level of statistical precision that would be appropriate for impact evaluation

### FREQUENCY OF INFORMATION NEED (for duration of survey stage or duration of real or potential impact)

A. At least once by end of survey, or annually if appropriate

B. Quarterly

C. Monthly

D. Weekly

E. Continually

F. Periodically. Either frequency of sampling in keeping with identification of the parameter when it undergoes some important change, or a fixed periodic schedule

### SPATIAL DISTRIBUTION OF INFORMATION NEED

I. Regional

II. General site area

III. Immediate site impact area (for particular parameter)

IV. Immediate site impact area (for the particular parameter) plus control area(s)

### BIOTIC PARAMETERS

IS. Identify important species or groups

Ab. Abundance. Estimates of numbers, biomass, or relative abundance, of important species or groups

S. Identify spatial distribution of life history stages of important species or groups at indicated frequency

SS. Identify significant existing stresses on or involving important species or groups

# TABLE 5. REPRESENTATIVE PHYSICAL, CHEMICAL, AND WATER QUALITY MATRIX

| SURVEY STAGE | Currents & Other Water Circulation Patterns | Flushing Rate | Existing Temperature Patterns | Bathymetric Conditions & Contours | Bottom Sediments & Sediment Transport | Salinity | D.O. of Water and Sediments | Turbidity | Dissolved Solids | pH | Nutrients | Man-made Chemical Stresses |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **INITIAL EVALUATION SURVEY** | 1,A,I | 1,A,I | 1,A,I | 1,A,I | 1,A,I | | | | | | | |
| **SITE SELECTION SURVEY** | 2,A,II | 2,A,II | 2,A,II | 2,A,II | 2,A,II | | | | | | | |
| **BASELINE SURVEY** | 3,E,III | 2,B,III | 3,E,III | 3,A,III | 3,A,III | 3,E,II | 3,C,III | 3,C,III | 3,C,III | 3,C,III | 3,C,III | 3,C,III |
| **SITE - PLANT DESIGN EVALUATION** | 3,E,III | 2,A,III | 3,E,III | 3,A,III | 3,A,III | 3,E,II | | | | | | |
| **SITE EXPLORATION MONITORING** | | | | | 3,A,III | 3,E,II* | 3,A,IV* | 3,E,III* | 3,A,IV* | 3,A,IV* | 3,A,IV* | 3,A,IV* |
| **CONSTRUCTION MONITORING** | | | | 3,A,III** | 3,A,III** | 3,E,II* | 3,B,IV | 3,E,IV | 3,B,IV | 3,B,IV | 3,B,IV | |
| **PREOPERATION SURVEY** | 3,B,II** | 3,B,II** | 3,E,III** | 3,A,III** | 3,A,III** | 3,B,II** | 3,C,IV | 3,C,IV | 3,C,IV | 3,C,IV | 3,C,IV | 3,C,III |
| **STARTUP MONITORING** | 3,E,III | 3,E,III | 3,E,III | | 3,A,III | 3,E,II | 3,A,IV*** | 3,E,IV*** | 3,A,IV*** | 3,A,IV*** | 3,A,IV*** | 3,E,III |
| **OPERATING MONITORING** | Monitoring Program Limits Determined By Regulatory Requirements | | | | | | | | | | | |

*If potential change due to exploratory activities is possible.

**Assess changes that might occur since time of site selection survey.

***Should be done near end of test and over at least one tidal cycle.

## KEY TO CODES LISTED IN MATRIX

SOURCE OF INFORMATION NEED

1. From existing sources
2. Estimates from field observations if not adequately available from No. 1
3. Quantitative from field studies with level of statistical precision that would be appropriate for impact evaluation

FREQUENCY OF INFORMATION NEED (for duration of survey stage or duration of real or potential impact)

A. At least once by end of survey, or annually if appropriate

B. Quarterly

C. Monthly

D. Weekly

E. Continually

F. Periodically. Either frequency of sampling in keeping with identification of the parameter when it undergoes some important change, or a fixed periodic schedule

SPATIAL DISTRIBUTION OF INFORMATION NEED

I. Regional

II. General site area

III. Immediate site impact area (for particular parameter)

IV. Immediate site impact area (for the particular parameter) plus control area(s)

omit

II-A-12a

# THERMAL GUIDLINES AS THEY APPLY TO THE STEAM ELECTRIC POWER GENERATING INDUSTRY

R. Schaffer

U. S. Environmental Protection Agency

Washington, D. C.

4-45-10

II-A-25

# EVALUATING THE ADVERSE IMPACT OF COOLING WATER INTAKE STRUCTURES ON THE AQUATIC ENVIRONMENT

S. L. BUGBEE
U. S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. U.S.A

## ABSTRACT

The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) require under section 316 (b) that cooling water intake structures reflect best technology available for minimizing adverse environmental impact through entrainment and impingment.

The process for evaluating existing and proposed intakes is discussed. The method of evaluation includes decision criteria which will identify the magnitude of any adverse environmental impact.

## INTRODUCTION

In most cases under section 316 (b), studies will be needed to evaluate the impact of cooling water intake structures on the aquatic environment and allow for determination of the best technology available for minimizing adverse environmental impact. The 1972 amendments to the Federal Water Pollution Control Act (P.L. 92-500) requires in section 316 (b) that:

> "Any standard established pursuant to section 301 or section 306 of this Act and applicable to a point source shall require that the location, design, construction and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact."

Sections 301 and 306 of the Act refer to the development of effluent limitations and dates for achievement of various standards of performance for existing and new sources of waste discharges. The steam-electric generating point source category is the largest user of cooling water in the United States. Other categories of point source dischargers such as iron and steel and petrochemicals for which intakes withdraw a major portion for cooling water would also require such a determination.

The overall goal of conducting intake studies should be to obtain sufficient information on environmental impact to aid in determining whether the technology selected by the company is the best available to minimize adverse environmental impact. In the case of existing plants, this goal will be accomplished by providing reliable quantitative estimates of the damage that is or may be occurring and projecting the long-range

60<

SLB

effect of such damage to the extent reasonably possible. In the case of proposed intakes, reliable estimates of any future damage are to be obtained through the use of historical data, pre-operational models, and the operating experience of other plants. The environment-intake interactions in question are highly site specific and the decision as to best technology available for intake design, location, construction, and capacity must be made on a case-by-case basis.

## STATEMENT OF THE PROBLEM

Cooling water intakes can adversely impact aquatic organisms basically in two ways. The first is entrainment, which is the taking in of organisms with the cooling water. The organisms involved are generally of small size, dependent on the screen mesh size, and include phyto- and zooplankton, fish eggs and larvae, shellfish larvae, and many other forms of aquatic life. As these entrained organisms pass through the plant they are subjected to numerous sources of damage. These include mechanical damage due to physically contacting internal surfaces of pumps, pipes and condensers; pressure damage due to passage through pumps; shear damage due to complex water flows; thermal damage due to elevated temperatures in condenser passage; and toxicity damage caused by the addition of biocides to prevent condenser fouling and other corrosives.

The second way in which intakes adversely impact aquatic life is through entrapment-impingement. This is the blocking of larger entrained organisms that enter the cooling water intake by some type of physical barrier. Most electric generating plants have screening equipment (usually 3/8" mesh) installed in the cooling water flow to protect downstream equipment such as pumps and condensers from damage or clogging. Larger organisms, such as fish which enter the system and cannot pass through the screens, are trapped ahead of them. Eventually, if a fish cannot escape or is not removed, it will tire and become impinged on the screens. If impingement continues for a long time period the fish may suffocate because the water current prevents gill covers from opening. If the fish is impinged for a short period and removed, it may survive; however, it may lose its protective slime and/or scales through contact with screen surfaces or from the high pressure water jets designed to remove debris from the screens. Delayed mortality to many species of fish following impingement may approach 100 percent. For some species of fish, the intake represents a double jeopardy situation where the same population will be subject to increased mortality through entrainment of eggs and larvae and additional mortality to juveniles and adults through impingement.

The data presently available on the magnitude of entrainment losses at existing electric generating stations, although just beginning to accumulate, reveals very large number of fish passing through some facilities. Results of one of these studies, conducted at the Detroit Edison plant on Lake Erie near Monroe, Michigan, indicate that 400-800 million fish larvae may have passed through that plant during April-August 1974.[1]

Other studies have shown that mortality may be high among fish larvae that pass through plant cooling systems [2,3] due mainly to mechanical damage or shearing forces.[4,5] The circulating pump has been indentified as the most likely site for mechanical damage. Coutant and Kedl[6] in a simulation study have demonstrated that the condenser tubes are an unlikely site for mechanical damage to occur.

A large amount of data are available on the magnitude of entrapment-impingement losses at cooling water intakes. The data available on fish losses at cooling water intakes in the Great Lakes area have been summarized by Edsall.[7] He reported the following losses:

> About 92,000 pounds of gizzard shad at the Ontario Hydro Lambton plant on the St. Clair River in 6 weeks during December 1971 - January 1972; 82,187 pounds (nearly 1.1 million individuals at the Detroit Edisons plant on Lake Erie near Monroe, Michigan between April 1972 and March 1973, when the plant was operating at less than maximum capacity; 36,631 pounds (584,687 fish) at the Consumers Power Company's Palisades plant on Lake Michigan between July 1972 and June 1973, when the plant was operating at about 68 percent of its total capacity (the plant is now closed cycle); an estimated 1.2 million fish (no weight data given) at Commonwealth Edison's Waukegan (Illinois) plant on Lake Michigan between June 1972 and June 1973; 150,000 pounds of fish at the Ontario Hydro Pickering plant on Lake Ontario in April-June 1973; 659,000 fish (weight unavailable) at the Nine Mile Point plant generating unit number one on Lake Ontario during intermittent sampling from January-December 1973, representing an estimated total of about 5 million fish at unit one for that period; and about 67,950 pounds (929,000 fish) at Commonwealth Edison's Zion plant near Zion, Illinois, on Lake Michigan during September-December 1973 and March-June 1974, when the monthly cooling water flow averaged only about 45 percent of the maximum capacity.

Approximately 14,000 fish of 44 species were impinged in 1974 at the Northern States Power Prairie Island Plant on the Mississippi River.[8] The Commonwealth Edison Company's Quad Cities Plant, also on the Mississippi River, impinged an estimated 1.8 million fish during 1974.[9]

The extent of fish losses of any given quantity needs to be considered on a plant-by-plant basis, in that the language of section 316 (b) of

P.L. 92-500 requires cooling water intakes to "minimize adverse environmental impact." Regulatory agencies* should clearly recognize that some level of intake damage can be acceptable if that damage represents a minimization of environmental impact.

## INFORMATION REQUIREMENTS

The development of 316 (b) programs is a new procedure for many agencies and user groups. The process for evaluating existing intakes (Figure 1) is intended to be flexible so that the data requirements can be revised based on an agency determination of the potential for adverse impact and the availability of data on the plant's intake. It is expected that for some existing plants, sufficient data may already exist to make further studies unnecessary for a decision regarding best technology available. The process for new intakes (Figure 2) is more extensive because of requirements for data acquisition and models prior to site review and approval by the appropriate agency. Proper intake siting, in many cases, is the only way of minimizing adverse environmental impact. To obtain the necessary pre-siting perspective, the utilization of valid historical data and local knowledge is essential. A one-to-three-year biological survey is required to obtain, in a preliminary fashion, the necessary data for assessment of environmental impact. A one-year survey is generally of limited value. However, in circumstances where substantial valid historical data can be presented and the intake can be represented as having low potential impact, a one-year survey may be acceptable. A decision as to the appropriate number of years of pre-operational data that are necessary will be made by the agency upon the submission of proposed study plans and their justification. The type and extent of biological data appropriate in each case will be determined by the actual or anticipated severity or adverse environmental impact. Since the expected impact will vary, it is not expected that each case will require the same level of study.

A decision will be made at the outset by the agency as to whether the intake has high or low potential impact. Low potential impact intakes are generally those in which the volume of water withdrawn comprises a small percentage of the source water body segment and are located in biologically unproductive areas, or that have historical data showing no effect, or which have other considerations indicating reduced impact. High potential impact intakes will generally require extensive field surveys or models to elucidate potential total water body effects. New intakes will provisionally be considered high impact until data is presented in support of an alternate finding. The inclusion of several points in the flow chart for agency review

---

*Regulatory agencies, federal or state with the National Pollutant Discharge Elimination System (NPDES) authority, hereafter refer to as "agency."

and approval will ensure that all parties are in agreement as to the scope and specific details of work planned and will provide each party with a set of specific goals and schedules for completion. These review points should also ensure that studies address the important environmental and plant operational concerns of all parties, thereby resulting in timely and orderly completion. A further benefit from such review is that studies conducted throughout a water body segment can be coordinated so that methods utilized will result in a comparable data base. This uniform data base will allow for easier evaluation of any subsequent cumulative effect from all intakes operating on a water body.

## DECISION CRITERIA

Adverse aquatic environmental impacts occur whenever there will be entrainment or impingement damage as a result of the operation of a specific cooling water intake structure. The critical question is the magnitude of any adverse impact. The exact point at which adverse aquatic impact occurs at any given plant site or water body segment is highly speculative and can only be estimated on a case-by-case basis by considering the species involved, magnitude of the losses, years of intake operation remaining, ability to reduce losses, etc. The best guidance that can be provided to agencies in this regard would be to involve professional resource people in the decision-making process and to obtain the best possible quantitative data base and assessment tools for evaluation of such impacts.

Some general guidance concerning the extent of adverse impacts can be obtained by assessing the relative biological value of the source water body zone of influence for selected species and determining the potential for damage by the intake structure. For a given species, the value of an area is based on the following considerations:

1. principal spawning (breeding) ground;
2. migratory pathways;
3. nursery or feeding areas;
4. numbers of individuals present; and
5. other functions critical during the life history.

A once-through system for a power plant utilizes substantially more water from the source water body than a closed recirculating system for a similar plant and thus would tend to have a higher potential impact. A biological value-potential impact decision matrix for best intake technology available could be:

| | COOLING WATER FLOW (Relative to Source Water Body Segment) | |
|---|---|---|
| BIOLOGICAL VALUE | HIGH | LOW |
| HIGH | No | Questionable |
| Low | Questionable | Yes |

(1) An open system large volume intake in an area of high biological value does not represent best technology available to minimize adverse environmental impact and will generally result in disapproval.

Exceptions to this may be demonstrated on a case-by-case basis where, despite high biological value and high cooling water flow, involvement of the biota is low or survival of those involved is high, and subsequent reduction of populations is minimal.

(2) Generally, the combination of low value and low flow most likely is a reflection of best technology available in location, design, and operation of the intake structure. Exceptions to this could involve significantly affected rare and endangered species.

(3) Other combinations of relative value-impact present the most difficult problems. In such circumstances, the biological survey and data analysis requires the greatest care and insight in accomplishing the impact evaluation upon which the judgment of best technology available is based. A case-by-case study is required and local knowledge and informed judgment are essential.

Biological survey requirements should provide a sufficient data base to provide insight as to the best location, design, construction, and capacity characteristics appropriate for achieving minimal total impact.

A stepwise thought process is recommended for cases where adverse environmental impact from entrapment/impingement is occurring and must be minimized by application of best technology available:

The first step should be to consider whether the adverse impact will be minimized by the modification of the existing

> screening system.
>
> The second step should be to consider whether the adverse impact will be minimized by increasing the size of the intake to decrease high approach velocities.
>
> The third step should be to consider whether to abandon the existing intake and to replace it with a new intake at a different location and to incorporate an appropriate design in order to minimize adverse environmental impact.
>
> Finally, if the above technologies would not minimize adverse environmental impact, consideration should be given to the reduction of intake capacity which may necessitate installation of a closed cycle cooling system with appropriate design modifications as necessary.

Where environmental impact from entrainment must be minimized, reliance must be placed primarily on flow reduction and intake relocation as remedial measures:

> Reducing cooling water flow is generally an effective means for minimizing potential entrainment impact. In fact, this may be the only feasible means to reduce impact of entrainment where potentially involved organisms are in relatively large concentration and uniformly distributed in the water column. Entrapment and impingement may also be lessened with lower flow as proportionally fewer animals will be subject to contact with the intake structure; water velocities associated with the structure can be reduced, enhancing probability of survival if impinged or of escape if trapped. Reduction of flow is accomplished primarily by an increase in condenser temperature rise or through recirculating cooling systems. When cooling water flow is reduced, however, elevated temperature or the effects of an auxiliary cooling systems can increase the morality rate of the organisms that are entrained.

Site location measures may prove effective in areas of discontinuous, temporal or spatial occurrence (patchiness) of those species subject to entrainment (or entrapment/impingement).

Enhancing survivial of organisms once entrained in the cooling water system generally appears to be the least effective means for avoiding adverse impact; however, operational regimes have been developed to decrease mortality of entrained species where heat, chlorine or both exert the predominant impact. Realistic laboratory studies can lead to optimal time-temperature regimes for survival. The effects of biocides can be reduced by intermittent and "split-stream" chlorination procedures. Mechanical methods for cleaning cooling system components where feasible can eliminate or reduce the need for biocides. The mechanical stress of entrainment is, in many cases, the critical factor in organism survival with the pump the site of major damage. At present,

66<

little can be done to minimize mechanical impact although potentially harmful effects may possibly be reduced by pump redesign which incorporates low RPM, low pressure and wide clearance characteristics. Reducing velocity changes, pressure, and turbulence in the piping system should prove helpful. Entrainment screening techniques such as leaky dams may have application in some circumstances. Regardless of beneficial measures taken, many fragile forms will not survive entrainment.

In summary, the location of a power plant, or other cooling water use, coupled with the associated intake structure design, construction, and capacity results in a unique situation. While generalities may be useful, the optimal combination of measures effectively minimizing adverse impact on the biota is site and plant specific.

## ACKNOWLEDGEMENTS

The material for this paper was taken in part from the 316 (b) Technical Guidance Manual, U.S.E.P.A, which will be published later in 1977.

## REFERENCES

1. Nelson, D.D. and R.A. Cole. 1975. The Distribution and Abundance of Larval Fishes Along the Western Shore of Lake Erie at Monroe, Michigan. Thermal Discharge Series. Michigan State University. Technical Report 32.4. Institute of Water Reserve. 66p.

2. Beck, A.D. and D.C. Miller. 1974. Analysis of inner plant passage of estuarine biota. Proc. ASCE Power Div. Specialty Conf., Boulder, Colorado. August 12-14. 199-226.

3. Clark, J. and W. Brownwell. 1973. Electric Power Plants in the Coastal Zone: Environmental Issues. American Littoral Society Special Publication No. 7. 80 p.

4. Marcy, B.C., Jr. 1973. Vulnerability and survival of young Connecticut River fish entrained at a nuclear power plant. J. Fish. Res. Board Can. 30(8): 1195-1203.

5. Beck, A.D. and N.F. Lackey. 1974. Effects of passing marine animals through power plant cooling water systems. (Presented at Symposium on Effects of Nuclear Power Plants on the Marine Ecosystem. American Fisheries Society annual meeting Honolulu, Hawaii, September 7-11, 1974). U.S.E.P.A. Environmental Research Laboratory, Narragansett, Rhode Island.

6. Coutant, C.C. and R.J. Kedl. 1975. Survival of Larval Striped Bass Exposed to Fluid-Induced and Thermal Stresses in a Simulated Condenser Tube. Environmenal Sciences Division Publication No. 637. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 37 p.

7. Edsall, T.A. Electric Power Generation and Its Influence on Great Lakes Fish. (Presented at Second ICMSE Conference on the Great Lakes. Argonne National Laboratory, Argonne, Illinois. March 25, 1975.

8. Andersen, R.A. 1974. Fish Study, Impingement of Fishes and Other Organisms on the Prairie Island Plant Intake Traveling Screens. Environmental Monitoring and Ecological Studies Program, 1974 Annual Report, Volume 2 for the Prairie Island Nuclear Generating Plant near Red Wing, Minnesota. Northern States Power Company, Minneapolis, Minnesota. 755-824b.

9. Latviatis, B., H.F. Bernhard, D.B. McDonald. 1976. Impingement Studies at Quad-Cities Station, Mississippi River. (Presented at the Third National Workshop on Entrainment and Impingement. New York.)

## EXISTING INTAKES

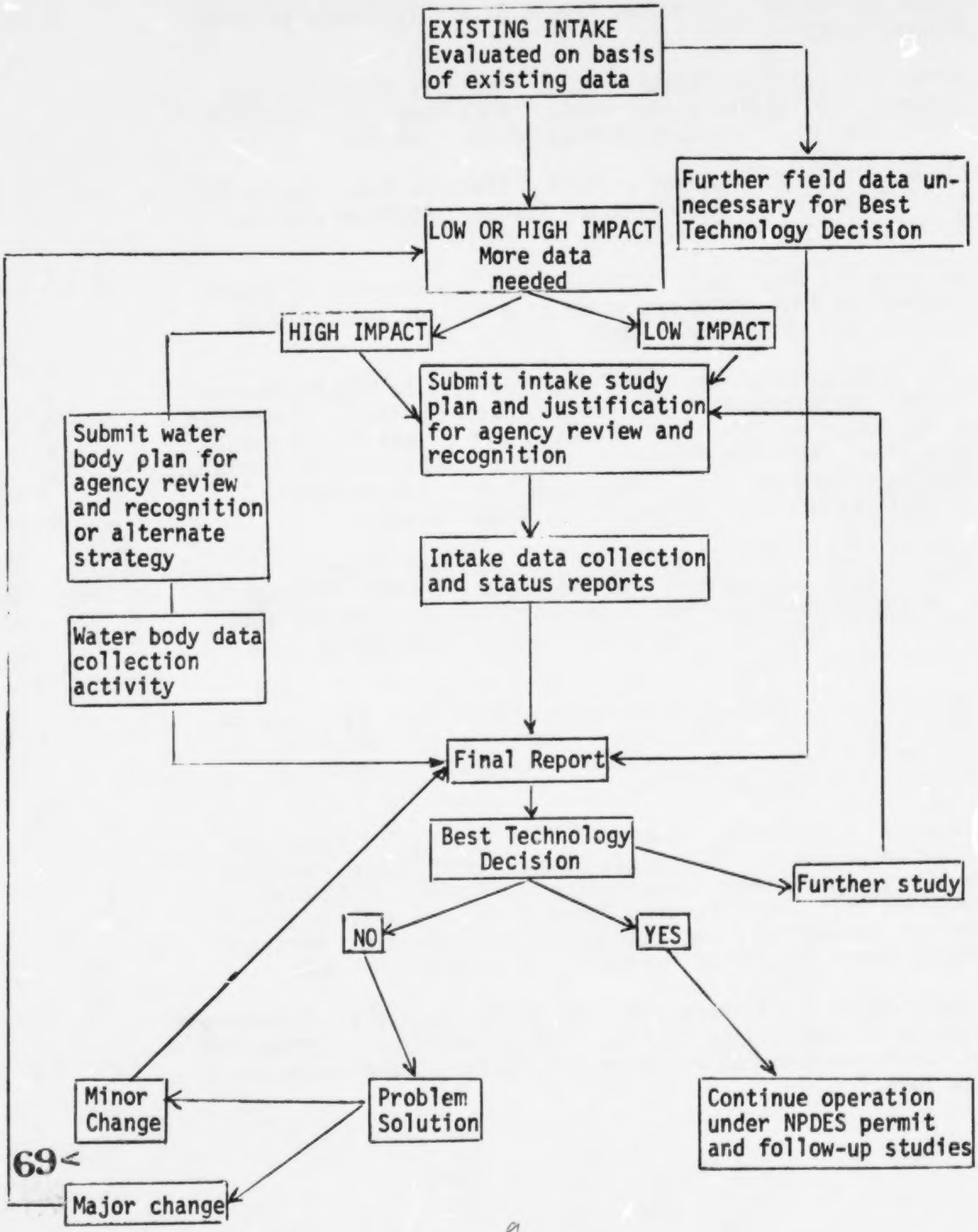

EXISTING INTAKE Evaluated on basis of existing data
Further field data unnecessary for Best Technology Decision
LOW OR HIGH IMPACT More data needed
HIGH IMPACT
LOW IMPACT
Submit intake study plan and justification for agency review and recognition
Submit water body plan for agency review and recognition or alternate strategy
Intake data collection and status reports
Water body data collection activity
Final Report
Best Technology Decision
Further study
NO
YES
Minor Change
Problem Solution
Continue operation under NPDES permit and follow-up studies
Major change

Figure 1. 316 (b) FLOW CHART

## NEW SOURCE INTAKES

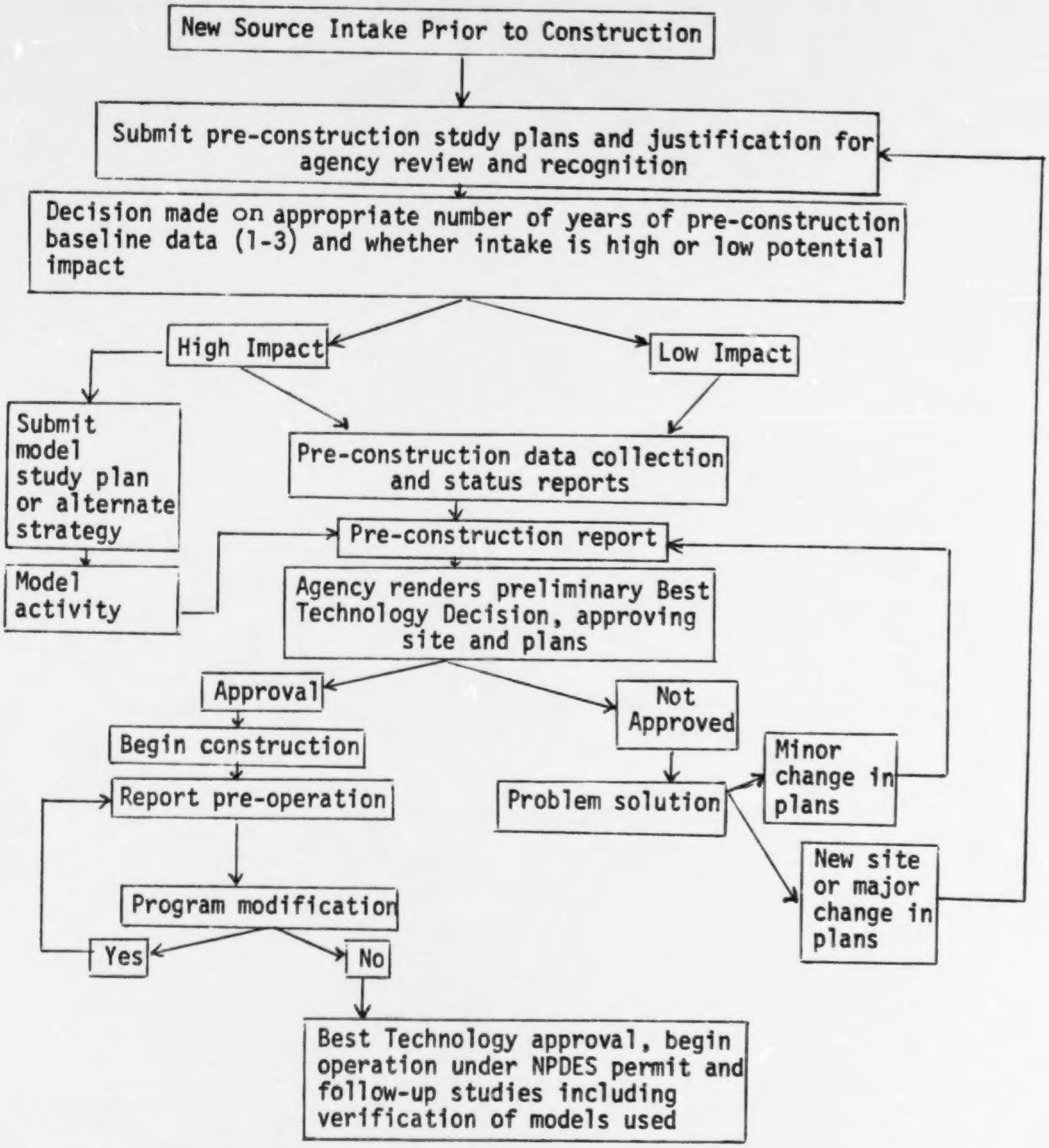

New Source Intake Prior to Construction
Submit pre-construction study plans and justification for agency review and recognition
Decision made on appropriate number of years of pre-construction baseline data (1-3) and whether intake is high or low potential impact
High Impact
Low Impact
Submit model study plan or alternate strategy
Model activity
Pre-construction data collection and status reports
Pre-construction report
Agency renders preliminary Best Technology Decision, approving site and plans
Approval
Not Approved
Begin construction
Report pre-operation
Program modification
Yes
No
Problem solution
Minor change in plans
New site or major change in plans
Best Technology approval, begin operation under NPDES permit and follow-up studies including verification of models used

Figure 2. 316 (b) FLOW CHART

# SESSION II-B

# ECOLOGICAL EFFECTS I

omit

II-B-39

# TEMPERATURE INFLUENCES ON GROWTH OF AQUATIC ORGANISMS*

Charles C. Coutant
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

## ABSTRACT

Temperature control profoundly affects the growth rates of aquatic organisms, and is essential for effective aquaculture. Characteristically, both low and high temperatures produce slow growth rates and inefficient food conversion while an intermediate temperature range provides rapid growth and efficient food conversion. Distinct, species-specific optimum temperatures and upper and lower temperatures of zero growth can often be defined. Thermal effects are greatly modified by amounts and quality of food. These data provide the basis for effectively using waste heat to create optimal conditions of temperature and ration for growing aquatic organisms commercially.

---

*Research supported by the Energy Research and Development Administration under contract with Union Carbide Corporation.

5-45-27

# COMPARISON OF ENVIRONMENTAL EFFECTS DUE TO OPERATION OF BRACKISH AND/OR SALT WATER NATURAL AND MECHANICAL DRAFT COOLING TOWERS

S. M. Laskowski and K. Woodard
Pickard, Lowe and Garrick, Inc.
Washington, D. C., U. S. A.

## ABSTRACT

The environmental impact which results from the operation of brackish or salt water natural draft or mechanical draft cooling towers at given sites has been studied. Effects related to discharge from the cooling tower exits such as length of the visible plume, ground fog, relative humidity increases, shadowing, salt deposition and icing were considered. One year of upper level hourly meteorological data were used to estimate potential effects. Results of the study support the conclusion that natural draft towers have the least environmental impact. The results of the study also point out the need for accurate drift rate and drift drop size distribution measurements since their proper characterization significantly affect the tower environmental impact assessment.

## SUMMARY

Effects resulting from the discharge of operating cooling towers of natural and/or mechanical draft types were estimated using the mathematical models described in References 1 and 2. The effects evaluated were length of the visible plume, ground fog, relative humidity increases, shadowing, salt deposition and icing. Other considerations such as aesthetics, noise, waste, etc. are not discussed in this report. Upper level hourly meteorological data used to estimate effects were obtained from a proposed nuclear power plant located on the eastern seaboard.

Results indicate that humid plume effects are not significantly different for the various types of towers considered, with the natural draft tower having the least environmental impact. They also indicate that salt drift deposition effects are significantly different between standard and state-of-the-art tower designs. This difference is mainly due to the drift rate and drift drop size distribution. The natural draft and the state-of-the-art round mechanical draft towers had the least environmental impact.

## CONCLUSIONS

Relative impacts on the environment for the various towers considered are presented in tabular form in Table 1. Ratings from 1 to 4 are given to each tower depending on its potential impact on the environment and are summarized in Table 2. The rating system is as follows:

| | |
|---|---|
| negligible impact | 1 |
| slight impact | 2 |
| moderate impact | 3 |
| severe impact | 4 |

Results of this study support the conclusion that natural draft towers have the least environmental impact, with the round mechanical draft towers equipped with state-of-the-art eliminators being second. The state-of-the-art mechanical draft towers and standard round mechanical towers are rated third place with the standard mechanical draft tower ranked lowest (e.g., having the highest potential for detrimental impact).

It should be pointed out that the potential effects due to drift (i.e., salt deposition and icing) are based on manufacturers' drift rate and drift drop size distribution. Changes in either the drift rate or in the drift drop size distribution will proportionally change the tower potential impact on the environment, specifically, the estimates of salt deposition will increase if the stated drift rates are not achieved.

## EFFECTS OF THE HUMID PLUME

The humid plume refers to the mixture of hot air and water vapor discharged from cooling towers. Under most meteorological conditions, the plume condenses upon leaving the towers and becomes visible (as condensed water vapor) until it is evaporated to invisibility after mixing with drier (unsaturated) colder air in the atmosphere. Humid plumes are not expected to have a significant influence on local meteorology. This is due primarily to the buoyancy of the plume causing it to rise several hundred meters above the tower base.

For the three tower types considered, plume effects are influenced by operating characteristics such as height of release, temperature and velocity at discharge, and tower configuration.

Plume effects investigated were:

Visible plume
Ground fog
Increase in ground relative humidity
Ice formation
Shadow

These effects were investigated using the Calabrese, Halitsky and Woodard [1] model programmed for computer. The model uses hourly meteorological data and takes into account local terrain profile. Data used to estimate effects described in this section were measured by instruments on a 340 ft meteorological tower at a proposed nuclear power plant located on the eastern seaboard for one year, unless otherwise specified.

## Visible Plume

The length of the visible plume depends on the temperature and humidity of the atmosphere. Colder and more humid weather is conducive to longer plumes. Most of the time the visible plume will extend only a short distance from the towers and will disappear by evaporation. On very humid days, when longer plumes are expected, there would probably be a naturally occurring overcast. On such occasions it is difficult to distinguish cooling tower plumes from the overcast. Using the Calabrese, et al computer model to compute plume dimensions for each hour of site data, isopleths of the number of hours of visible (overhead) plume length versus distance downwind have been estimated. Plume length calculations were made at over 40 distances in each of 16 direction sectors.

Results for each tower type are tabulated for two distances in Table 3. The table indicates, for example, that in the S direction the model predicts there will be about 350, 400 and 430 hours during the 12 month data period when the plume extends beyond the site boundary for the mechanical draft, round mechanical draft and natural draft types, respectively. Plumes are predicted to be visible for five miles in the SSW direction on 90, 100 and 100 hours for the same respective tower types. Other directions have a lower frequency for each of the two distances discussed above. These figures represent occurrences of visible plumes which may or may not be distinguishable from natural fog or overcast conditions. The number of hours of plumes distinguishable from overcast conditions may be considerably less than this; however, for comparative purposes these results are adequate.

Comparison of the results for the three tower types indicates little difference between them. This is because all are releasing approximately the same amount of water into similar atmospheric conditions. The fewer number of visible plume hours for the mechanical draft towers is probably due to the more "spread out" tower configuration. The other two types concentrate the plume initially into a smaller area. Colder temperatures at higher levels probably account for the slightly higher number of longer plumes for the natural draft towers which have a higher release level. Although there are some slight differences in plume predictions, we would not penalize any of the designs on this basis. The impact would be similar for each.

## Ground Fog

Observations made at operating mechanical draft towers indicate that wisps of the visible plume may intersect the ground near the tower under windy conditions due to building wake effects. However, observations verify that sustained fog does not occur beyond the wake boundary since the lower density of the warm moist plume compared with the surrounding atmosphere causes it to rise away from the ground. Thus, sustained ground fog due to mechanical draft tower operation would be rare beyond several hundred yards of the towers[3]. Visible portions of the plume are never observed at ground level near operating natural draft towers [3, 4]. Under very high wind conditions, plumes may extend downward one-half the tower height[3, 4, 5].

The previous statements were primarily concerned with "near field" effects. To determine potential ground level effects at greater distances, the computer model[1] was applied to the meteorological data. As shown in Table 3, the model predicted ground fog would result on about 14, 12 and 2 hours per year for the mechanical draft, round mechanical draft and natural draft types respectively between 20,000 and 40,000 meters in the SE direction which showed the highest ground fog potential. The model assumes there is ground fog when the plume plus the ambient atmosphere contains 0.02 gm/m$^3$ of water above saturation. A check of conditions for these hours showed that the ambient relative humidity was in excess of 97% as measured at the site meteorological tower, and that the atmosphere was stable. Under these conditions, it is expected that natural ground fog is likely in the area; therefore, the towers would have little additional impact.

Ambient relative humidity was set to 99% when instrumentation indicated higher values. This accounts for possible instrument errors and results in conservative estimates of fogging potential. If higher values of relative humidity were allowed, any tower moisture contribution would cause unrealistic estimates of fog for great distances.

Although little fog is predicted due to mechanical draft and round mechanical draft tower operation, the potential for it is certainly higher than for the natural draft towers. Therefore, mechanical draft and round mechanical draft towers should receive a small penalty compared with the natural draft towers.

### Increase in Ground Level Relative Humidity

The computer model [1] also calculates expected long-term average off-site increases in relative humidity (RH) out to a distance of 50 miles. Results of these calculations are given in Table 3. These peak off-site average incremental relative humidity increases (in %RH above ambient RH) were found to be about 0.086 and 0.083% RH for the mechanical draft and round mechanical draft towers in the SE direction at about 6 miles, and 0.027% RH to the NNE at about 40 miles for the natural draft tower.

Incremental hourly increases (not average annual, as above) in relative humidity have also been tabulated in Table 3 giving the number of hours during which the relative humidity was increased by various amounts for several distances in each direction. Incremental increases of between 5% and 10% RH were predicted at some off-site locations for 43, 42 and 2 hours respectively for the three tower types (mechanical draft, round mechanical draft and natural draft). These peak values occurred about 6 miles to the SE for the mechanical draft and round mechanical draft towers and about 12 miles to the NNE for the natural draft tower. For incremental increases over 1% RH, results were 143, 121 and 30 hours for the respective cooling towers as shown in Table 3. The higher values for the mechanical draft towers were attributed to their lower release elevation.

It is concluded that none of the three tower types would result in a significant impact as regards relative humidity increases even though the two mechanical draft towers showed a higher relative impact.

### Ice Formation Due to Condensed Plume

Most of the icing potential of a cooling tower is due to the condensate and drift droplets impinging on surfaces at or below freezing. Icing due to drift droplets is addressed in the drift section.

Condensate droplets are the small water drops (mass median diameter of about 10 μm) that travel with the humid plume (i. e., stay in the plume). When the plume meets an object, some of the drops will have enough inertia to cross the streamlines and hit the object where they are collected (e.g., aerodynamic capture). The collection efficiency of an object depends, among other parameters, on the size and shape of the object, and on the drop size and drop impingement velocity on the object[6]. The collection efficiency for drops of 10 μm is small (no greater than 44%).

Operation of either type of tower, under high wind speed conditions and low ambient temperatures may cause icing on thin structures located in the path of the plume if plume temperatures are below 32°F. Calculations made to estimate ice accumulation on 1.4 inch cylindrical structures give a maximum icing rate of 0.25 inch/hour, which decreases with increasing accumulation. Similar conditions but with ambient temperatures >32°F will result in water accumulation (wetting). One of the differences in the potential for icing between the various types of towers is the height at which the object needs to be in order to be located in the plume path. This is illustrated in Table 4. In this table plume centerline height is given for several potential icing conditions. For example, Table 4 shows that for a wind speed of 10 m/sec (case 2, ambient temperature = 20°F, relative humidity = 90%, neutral atmosphere) at 0.2 miles downwind from the tower, the plume centerline in a natural draft tower is about 950 ft (290 m) above ground, while the mechanical draft and round mechanical draft towers are 584 ft (178 m) and 561 ft (171 m), respectively. The assumed plume radii in the natural draft, mechanical draft and round mechanical draft towers are 338 ft (103 m), 300 ft (92 m) and 295 ft (90 m), respectively.* Thus, fewer structures or objects will be intersected by natural draft towers' plumes since the plumes are higher and, even under extreme high wind conditions, the plumes never reach below one-half the tower height[3, 5].

Beyond about 100 meters downwind from the towers, no significant difference is expected to exist between the mechanical draft and the round mechanical draft towers. Some difference is expected to exist closer in, due to the plume interaction with tower wake. Under those conditions, the mechanical draft tower is expected to experience stronger wake interactions.

* The potential for icing exists in the height range between the bottom and top of visible (condensed) plume.

78<

## Shadow

Ground level shadowing caused by the condensed humid (visible) plume is estimated using a computerized model. Hourly calculations of plume height, plume length, plume direction and time of day obtained as output from the Calabrese, et al [1] computer program are combined with hourly values of the sun's position in the calculation. Computation of the sun's position is based on equations of time and declination tables for the sun received from the Naval Observatory for 1968. The location of the sun is determined hourly based on local mean solar time. Input parameters for determining these local conditions are the site latitude and the difference between local time and standard time. Shadows are assumed to be cast when the sun's angle above the horizon is greater than 10° after sunrise and/or before sundown. The plume is represented by a line connecting the top of the stack with the end of the visible portion of the plume. The shadow is assumed to cover the entire direction sector if any part of a straight line projection of the plume is in the sector at the given distance. Shadow estimates resulting from a natural and a mechanical draft cooling tower were made for a northeastern site for the month of June. These estimates are shown in Figure 1 as the percent of available sunshine hours the shadow will extend the stated distance and direction. For example, Figure 1 shows that in the WNW sector 1% of the time the natural draft tower casts a longer shadow than the mechanical draft tower (1.6 miles versus 0.4). This difference is probably due to the difference in tower height (500 ft versus 60 ft, respectively). In all other sectors there is no significant difference between the two types of towers.

## DRIFT

A very small fraction of the brackish water circulating through the cooling tower will be carried as small droplets in the rising air which leaves the tower top. This drift rate fraction (defined as Kg of salt per second leaving the tower top divided by the Kg of salt per second circulating through the tower heat exchange section) averages about 1 to 2 x $10^{-5}$ (or .001 to .002%) for towers with good drift control systems, and from 3 x $10^{-5}$ - 1 x $10^{-4}$ for towers with standard eliminators. Drift rate variation with tower type are given in Table 5.

The rate at which drift salt deposits on the ground outside the tower (e.g., as Kg/Km$^2$-month) and the near ground air concentration of such salt (e.g., as $\mu$g/m$^3$) is a function of distance and direction from the tower and depends on:

a) Tower geometry and operating conditions
b) Mass drift rate (i. e., the drift rate fraction times the circulating rate)
c) Drift drop size distribution
d) Terrain profile
e) Ambient atmospheric conditions including wind direction, wind speed, relative humidity, stability and precipitation rate

These relationships have been characterized in a mathematical model described in References 4 and 5.

Computer calculations using the model follow the history of representative drift droplets of selected initial size and salinity from the time they leave the drift eliminators in the tower to the place where they deposite on the ground taking account of accretion and evaporation of water from each droplet, of the effect of gravity and air currents on their average motion, and of their statistical distribution in space (around average trajectories) due to turbulent dispersion. The model also accounts for the effect of precipitation (e.g., rainfall), the aerodynamic wake of the tower and local topography.

Salt Deposition Due to Drift

The computer model was used to estimate average dry deposition rates on the ground and near ground air concentration for salt as a function of direction and distance from the cooling tower for each of the three types of cooling tower. Figures 2 and 3 illustrate typical computer output.

The highest downwind annual average, off-site, dry deposition rate and airborne concentration of salt, estimated in this way for the three types of towers studied, are summarized in Table 6 and shown in Figure 4. Table 6 and Figure 4 indicate, for example, that operation of mechanical draft towers equipped with standard design drift eliminators will result in salt deposition rates and concentrations which are up to a factor of $10^4$ higher than those resulting from operation of natural draft towers. No significant difference exists between the salt estimate for state-of-the-art towers of either the natural or round mechanical draft design. Peak values for these towers are about one order of magnitude lower than those obtained for the state-of-the-art mechanical draft towers. The significant difference between the various tower types is mainly due to the drift rate and drift drop size distribution given by the manufacturers. Changes in these two parameters will significantly change the predicted drift effects.

80<

The estimates summarized in Table 5 and Figures 2, 3 and 4 are based on the following:

a) Tower Geometry and Operating Conditions

1. Average air exit speed:
   natural draft = 5.65 m/sec
   mechanical draft = 9.55 m/sec
   round mechanical draft = 7.02 m/sec

2. Basin water salinity: 10,000 ppm sea salt
   Other operating conditions are described in Table 5.

b) Terrain Profile

70 ft is subtracted from the effective height of the natural draft tower (in calculations) to account for nearby terrain higher than the tower base.

c) Mass Drift Rate

Natural draft: 14./28. Kg of salt/hour/tower, equivalent to a drift rate fraction of 0.001/0.002% of the circulating water flow rate

Mechanical draft: 118.9/11.89 Kg of salt/hour/unit (2 towers per unit) equivalent to a drift rate of 0.01% and 0.001%, respectively, of the circulating water flow rate

Round mechanical draft: 35.67 and 11.89 Kg of salt/hour/unit (2 towers per unit) equivalent to a drift rate of 0.003% and 0.001%, respectively, of the circulating water flow rate.

d) Drift Drop Size Distribution

Table 7 represented the assumed drift drop size distribution just downstream of the eliminators.

e) Atmospheric Conditions

Data used were that measured for each hour by instruments on the meteorological tower at an eastern site for one year of record. Data used in the calculations were taken from the wind speed and direction instruments at 340 ft above grade. Temperature difference for determining stability was measured between the 340 ft and 200 ft levels and precipitation from an instrument near the ground. Relative humidity was derived from dew point and dry bulb temperature measurements at 340 ft.

## Ice Formation Due to Drift

If the drift is high, ice formation on the ground and on structures may be caused at low ambient temperatures and/or low ground temperatures and low structure temperature.

The accumulation of ice on the ground and on surfaces outside the tower is a function of distance and direction from the tower and depends on the same parameters that influence salt deposition rate by drift. These parameters are described above. In addition, ice accumulation on structures depends on the drift drop collection efficiency of the object. The drift drop collection efficiency of an object depends on the size of the drops and the shape and dimensions of the object and the drop impingement velocity on the object. These relationships have been characterized in the mathematical model described in Reference 8 and have been incorporated into a computer model.

The computer model was used to estimate the ice accumulation on the ground and on various structures as a function of time at selected distances from the towers, for each of the 16 discrete sectors used to represent the entire compass (360°) for the winter month of January. These estimates are summarized in Table 8 for the sector with highest accumulation for each of the towers studied. Figure 5 illustrates typical computer output for the sector with the highest accumulation. As can be seen from these estimates, ice accumulation resulting from operation of mechanical draft and round mechanical draft were up to two orders of magnitude higher than those expected for natural draft towers. In the case of the mechanical draft towers, the highest accumulation was 2.6 cm while in the round mechanical draft tower, it did not exceed .01 cm (basis: one unit).

## RESULTS

The effects on the environment of the various towers considered have been compared and the results are summarized in a tabular form in Table 1. Ratings from 1 to 4 are given to each tower depending on its potential impact on the environment. The rating is defined in Conclusions. The reasoning for each rating is briefly described below.

1) Elevated visible plume occurrence: No significant difference is expected on the frequency of occurrence of the extend (length) of the visible plume (a rating of 1 to all type towers). However, the visible plume from natural draft towers is expected to be at a higher elevation than those resulting from the mechanical draft towers (rectangular and round). No penalties have been applied.

82<

Rating: natural draft = 1
mechanical draft = 1
round mechanical draft = 1

2) Induced ground level fog: Natural draft tower will induce negligible fog at either on-site or off-site locations. Mechanical draft towers of either the round or rectangular configuration are expected to occasionally induce ground level fog, with the rectangular type having more frequent contributions. However, as seen in Table 3, the total number of hours predicted for either type is small.

Rating: natural draft = 1
mechanical draft = 2
round mechanical draft = 2

3) Increases in relative humidity: The mechanical draft towers (rectangular and round) estimated contribution to ambient relative humidity is greater than the contribution estimated for the natural draft towers (see Table 3 ). However, the results indicate that none of the three tower types would contribute to a significant increase to the ambient values. Therefore, the rating is the same for the three types of towers.

Rating: natural draft = 1
mechanical draft = 1
round mechanical draft = 1

4) Icing due to the humid plume: Experience and predictions indicate plumes from natural draft towers do not reach below one-half the tower height even under extreme (high wind speed) condition. Consequently, icing on the ground and/or on structures lower than one-half the tower height is not expected to occur. Icing potential for the mechanical type towers is greater, because the plume exits the tower at a lower elevation. Thus, ice formation on structures such as transmission lines and tree branches (ice formation on massive structures due to condensation will not occur because the collection efficiency of these structures for small drops is zero), located in the path of the plume may be caused when condensate droplets intersect these structures.

Rating: natural draft = 1
mechanical draft = 1
round mechanical draft = 1

5) Shadow: No significant difference was observed in the estimates of the percent available sunshine hours that the shadow cast by either type of tower will extend a given distance. The estimates also show that the shadowing potential of either type of tower is small. Therefore, estimates were not made for the round mechanical draft tower as its frequency of shadowing will probably be between that of the mechanical draft and that of the natural draft. No penalties have been applied to any of the towers.

Rating: natural draft = 1
mechanical draft = 1
round mechanical draft = 1

6) Salt deposition: Estimated deposition rate and near ground airborne concentration of salt for the natural draft tower are up to four orders of magnitude smaller than those estimated for the standard mechanical draft towers and up to one order of magnitude smaller than those for the state-of-the-art mechanical draft and the standard round mechanical draft tower. The state-of-the-art round mechanical draft is within a factor of 2 of the values estimated for the natural draft.

Rating: natural draft = 1

state-of-the-art round mechanical draft = 1

standard round mechanical draft = 2

state-of-the-art mechanical draft = 2

standard mechanical draft = 4

7) Icing due to drift: Icing on the ground or on structures near the ground due to drift from the natural draft and from the state-of-the-art round mechanical draft tower is not expected to exceed 0. 002 cm. Icing due to draft from the state-of-the-art mechanical draft tower and standard round mechanical draft is not expected to exceed 0. 02 cm. Icing from the standard mechanical draft towers is expected to be about 0. 2 cm on the ground and up to 1 to 2 cm on structures near the ground. Thus, icing due to drift is expected to have no significant effect on the environment except from operation of standard mechanical draft towers.

Rating: natural draft, state-of-the-art round mechanical draft = 1

standard round mechanical draft, state-of-the-art mechanical draft = 2

standard mechanical draft = 4

It should be point out that Table 2 does not include rating of the tower according to commercial experience and verification of drift rate and drift drop size distribution. A change in either of these two parameters will significantly change the results presented in this study, specifically the effects due to drift (salt deposition and icing).

## REFERENCES

1. Calabrese, R. V., Halitsky, J. and Woodard, K., "Prediction of Temperature and Moisture Distributions in Cooling Tower Plumes, presented at the Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, California, September 1974.
2. Laskowski, S. M., "A Mathematical Transport Model for Salt Distribution from a Salt Water Natural Draft Cooling Tower", presented at the Cooling Tower Symposium, University of Maryland, 1974.
3. Bogh, P., Hopkirk, R., Hunod, H., and Zuend, H., "A New Method of Assuming the Environmental Effects of Cooling Towers as First Applied to the Kaiser augst and Leibstadt Nuclear Power Plant", presented at the International Nuclear Industries Fair, October 1972, Basel, Switzerland.
4. Spurr, G., "The Magnitude of the Problem of Thermal Discharge from Nuclear Power Plants", Central Electricity Generating Board, England, September 1972.
5. Hoydysh, W., Experimental Work for the General Public Utilities Corporation, Forked River Environmental Report, 1972.
6. Ranz, W. E., "Principles of Inertial Impaction", Dept. of Eng. Res., Penn State Univ., Bulletin No. 66, Technical Report No. 1, U. S. Public Health Service Research Grant S-19, December 1956.
7. Laskowski, S. M., "A Mathematical Transport Model for Salt Distribution from a Salt Water Natural Draft Cooling Tower - Part II, presented at the Symposium on Atmospheric Diffusion and Air Pollution, sponsored by the American Meteorological Society, Santa Barbara, California, September 1974.
8. Laskowski, S. M. and Woodard, K., "Environmental Effects of Atmospheric Discharges from Natural Draft Cooling Towers at Indian Point", report to Consolidated Edison Co., published as Appendix B in the "Economic and Environmental Impacts of Alternative Closed-cycle Cooling Systems for Indian Point Unit No. 2", Vol. 2, December 1974 (Docket No. 50-247).

86<

## TABLE 1
## COMPARISON OF COOLING TOWER CONSIDERED

| | Natural Draft | | Mechanical Draft | | Round Mechanical Draft | |
|---|---|---|---|---|---|---|
| | 0.001% D.R. | 0.002% D.R. | Standard | State-of-the-Art | Standard | State-of-the-Art |
| **Size** Height, ft<br>Exit diameter, ft | 375.<br>190. | | 65.<br>cell = 31.5, each tower approximately 75. ft wide, 469. ft long | | cell = 36. ft; Overall tower = 285. ft | |
| No. of towers per generating unit | 1 | | 2<br>(13 cells per tower) | | 2<br>(13 cells per tower) | |
| Elevated visible plume length: no. of hours exceeding stated distance in most frequent direction. Distances: 1 mile<br>5 miles<br>25 miles | 420 hours, several<br>100 hours, S<br>39 hours, SSW | | 350 hours, SE<br>90 hours, S<br>44 hours, SSW | | 400 hours, SE<br>100 hours, S<br>44 hours, SSW | |
| Ground level fog - maximum hours in one direction | 1 hour | | 14 hours | | 12 hours | |
| Shadowing - percent of available sunshine hours extend state distance and direction | 1%, 1.6 miles, WNW | | 1%, 0.4 mile, WNW | | Not estimated. Expected to be within the values obtained for the other two tower types | |
| Maximum annual average salt deposition rate (Kg/Km$^2$-months) per generating unit in stated sector | 20.7 at 0.75 miles SW<br>5.9 at 2.5-3 miles SW | 21.5 at 0.75 miles SW<br>8.3 at 3. miles SW | 8.7x10$^4$ at .16 miles SW<br>817. at 1.25 miles SW | 26. at .31 miles SW<br>141.3 at 2.5 miles SW | 142. at .75 miles SW<br>66 at 1.25 miles SW | 8.5 at .75 miles SW<br>5.1 at 3 miles SW |
| Maximum annual average airborne concentration ($\mu g/m^3$) of salt per generating unit in stated sector | 0.1 at .75 miles SW<br>.02 at 3. miles SW | .018 at .16 miles SW<br>.036 at 75. miles SW | 12.8 at .16 miles SW<br>.57 at 1.25 miles SW | .03 at 1 miles SW<br>.16 at 2.5 miles SW | .07 at 0.75 miles SW<br>0.1 at 1.5-2 miles SW | .009 at .75 miles SW<br>.024 at 3 miles SW |
| Ice | None expected | | Frequent near the tower, on structures and on ground | Occasionally near the tower, on structures located in plume path, ground icing infrequent | Occasionally near the tower, on structures located in plume path; ground icing infrequent | None expected |
| Commercial experience | Many, using fresh water tower. First brackish water tower started operating in 1975. | | Many, using fresh water tower<br>Several using salt water | | First fresh water tower went into operation in 1975. No salt water experience. | |
| Experimental verification of drift and drift drop size distribution | Drift rate verified in operating plants and in test units. Drift drop size distribution has test verification | | Drift rate and drop size distribution verified in operating plants and test facilities | Not verified in operating plant. Drop size distribution not confirmed | Drift rate verified in operating plant. Drop size distribution not verified | None in operating plant. Manufacturer tests only. No information has been released |

88^

## TABLE 2

## RATING OF THE COOLING TOWERS CONSIDERED

| Impact Rating: | | |
|---|---|---|
| | negligible | 1 |
| | slight | 2 |
| | moderate | 3 |
| | severe | 4 |

| Tower Effect | Natural Draft | Mechanical Draft | | Round Mechanical Draft | |
|---|---|---|---|---|---|
| | | Standard | State-of-the-Art | Standard | State-of-the-Art |
| Elevated visible plume (aircraft hazard, aesthetics) | 1 | 1 | | 1 | |
| Ground level fog | 1 | 2 | | 2 | |
| Icing due to humid plume | 1 | 2 | | 2 | |
| Increases in relative humidity | 1 | 1 | | 1 | |
| Shadowing | 1 | 1 | | 1 | |
| Salt deposition | 1 | 4 | 2 | 2 | 1 |
| Icing due to drift | 1 | 4 | 2 | 2 | 1 |
| TOTAL | 7 | 15 | 11 | 11 | 9 |

## TABLE 3

## RESULTS OF COOLING TOWER COMPARISON: HUMID PLUME EFFECTS

| Tower Effect | Mechanical Draft | Round Mechanical Draft | Natural Draft |
|---|---|---|---|
| Max. hrs. of elevated visible plume in worst direction at 1 mile | 350 | 400 | 430 |
| Direction | S | S | S |
| Max. hrs. of visible plume in worst plume direction at 5 miles | 90 | 100 | 106 |
| Direction | SSW | SSW | SSW |
| Max. hrs. of visible plume in worst direction at 25 miles | 42 | 44 | 43 |
| Direction | SSW | SSW | SSW |
| Max. hrs. ground fog in one direction | 14 | 12 | 2 |
| Min-Max. dist. for condition in worst direction (meters) | 2.0E4-4.0E4 | 2.0E4-4.0E4 | 3.0E4-7.0E4 |
| Direction | SE | SE | SE |
| Maximum average % RH increase | 0.086 | 0.083 | 0.027 |
| Distance, m | 8,000 | 9,000 | 70,000 |
| Direction | SE | SE | NNE |
| Maximum % RH increase for peak hour | 10 | 10 | 10 |
| Number of hrs with % RH increase between 5% and 10% | 43 | 42 | 2 |
| Distance, m | 10,000 | 10,000 | 20,000 |
| Direction | NW | NW | NNE |
| Number of hrs. with % RH above 1% increase | 143 | 121 | 30 |
| Distance, m | 22,000 | 22,000 | 50,000 |
| Direction | NNE | WNW | NE |

## TABLE 4

## RESULTS OF COOLING TOWER COMPARISONS: HUMID PLUME ICING POTENTIAL

Basis: atmospheric stability = 4 (neutral)

| Ambient | | | | Natural Draft | | | Mechanical Draft | | | Round Mechanical Draft | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp. (°F) | Wind Speed (m/sec) | Relative Humidity (%) | Downwind Distance (m) | Centerline Height (m) | Radius (m) | Centerline* Liq. Water ($g/m^3$) | Centerline Height (m) | Radius (m) | Centerline* Liq. Water ($g/m^3$) | Height (m) | Radius (m) | Centerline* Liq. Water ($g/m^3$) |
| 20 | 10 | 98 | 200 | 259 | 95 | 1.88 | 144 | 84 | 3.4 | 139 | 82 | 2.7 |
| 20 | 10 | 90 | 300 | 292 | 103 | 1.6 | 178 | 92 | 3.0 | 171 | 90 | 2.4 |
| 32 | 20 | 98 | 200 | - | - | - | 80 | 70 | 2.3 | 78 | 69 | 2.1 |
| 32 | 20 | 90 | 300 | - | - | - | 96 | 78 | 1.9 | 93 | 77 | 1.7 |
| 20 | 5 | 98 | 200 | - | - | - | 268 | 141 | 2.8 | 256 | 149 | 2.5 |
| 20 | 5 | 90 | 300 | - | - | - | 335 | 154 | 2.5 | 320 | 153 | 2.0 |

*Liquid water content is a maximum at plume centerline and radially decreases to zero at the plume boundary.

90<

## TABLE 5

## ASSUMED DESIGN OPERATING CONDITIONS FOR THE THREE TYPES OF COOLING TOWERS UNDER CONSIDERATION

Basis: Cooling Capacity for One Nuclear Generating Unit at Full Power

---

| | Mechanical Draft | | Natural Draft |
|---|---|---|---|
| | Rectangular | Round | |
| Design wet bulb ($^{\circ}$F)<br>Design wet bulb ($^{\circ}$F) | 78 | 78 | 78 |
| Design range ($^{\circ}$F) | 30.4 | 30.4 | 25 |
| Design flow (gpm) | 527000 | 527200 | 619000 |
| Overall tower height (ft) | 65 | | 375 |
| Full power heat load (BTU/hr) | $8\text{x}10^9$ | $8\text{x}10^9$ | $8\text{x}10^9$ |
| Number of towers per unit | 2 | 2 | 1 |
| Number of cells per tower | 13 | 13 | -- |
| Discharge velocity, m/sec | 9.55 | 7.02 | 5.65 |
| Drift rate, % design flow: | | | |
| Standard | 0.01 | 0.003 | |
| State-of-the-art | 0.001 | 0.001 | 0.001/0/002 |
| Drop size distribution | See Table 7 | | |

## TABLE 6

## RESULTS OF COOLING TOWER COMPARISONS: SALT DRIFT DEPOSITION

Basis: Number of Generating Units: One
Direction: Winds from SW

### NATURAL DRAFT

| Distance, Miles | Salt Deposition Rate Kg/Km$^2$-month 0.001% D.R. | Salt Deposition Rate Kg/Km$^2$-month 0.002% D.R. | Near Ground Airborne Concentration ($\mu g/m^3$) 0.001% D.R. | Near Ground Airborne Concentration ($\mu g/m^3$) 0.002% D.R. |
|---|---|---|---|---|
| 0.16 | 7.2 | 13.5 | .001 | .018 |
| 0.75 | 20.7 | 21.5 | .01 | .012 |
| 1.24 | 7.9 | 8.6 | .011 | .014 |
| 3. | 5.9 | 8.3 | .02 | .031 |
| 5. | 4.8 | 7.5 | .019 | .034 |
| 10. | 2.8 | 5.1 | .014 | .026 |

### MECHANICAL DRAFT

| | Salt Deposition Rate Kg/Km$^2$-month Standard | Salt Deposition Rate Kg/Km$^2$-month State-of-the-Art | Near Ground Airborne Concentration ($\mu g/m^3$) Standard | Near Ground Airborne Concentration ($\mu g/m^3$) State-of-the-Art |
|---|---|---|---|---|
| 0.16 | $8.7 \times 10^4$ | 7.7 | 12.8 | .007 |
| 0.75 | 198. | 1.8 | .07 | .005 |
| 1.24 | 817. | 24. | .57 | .07 |
| 3. | 171. | 74.8 | .22 | .1 |
| 5. | 11.7 | 4.5 | .04 | .02 |
| 10. | 2. | .8 | .01 | .004 |

### ROUND MECHANICAL DRAFT

| | | | | |
|---|---|---|---|---|
| 0.16 | 89. | 5. | .04 | .006 |
| 0.75 | 142. | 8.5 | .07 | .009 |
| 1.25 | 66. | 6.1 | .1 | .014 |
| 3. | 28. | 5.1 | .1 | .024 |
| 5. | 15. | 3.1 | .07 | .016 |
| 10. | 5. | 1.3 | .03 | .007 |

92<

## TABLE 7

## DROP SIZE DISTRIBUTION VARIATION WITH TOWER TYPE

| | | | FRACTION OF TOTAL MASS IN GROUP | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Natural Draft | | Mechanical Draft | | Round Mechanical Draft | |
| Group | Nominal Drop Diameter (μm) | Range of Diameter (μm) | State-of-the-art 0.001% Drift Rate | State-of-the-art 0.002% Drift Rate | Standard | State-of-the-art | Standard | State-of-the-art |
| 1 | 50 | 10-75 | .22 | 0.35 | .12 | .88 | .67 | .88 |
| 2 | 100 | 75-125 | .42 | 0.44 | .05 | .08 | .17 | .08 |
| 3 | 150 | 125-175 | .21 | 0.14 | .04 | .02 | .08 | .02 |
| 4 | 200 | 175-240 | .13 | 0.06 | .05 | .014 | .045 | .014 |
| 5 | 280 | 240-325 | .012 | 0.006 | .05 | .004 | .021 | .004 |
| 6 | 450 | >325<br>325-580 | .008 | .004 | .535 | .002 | .014 | .002 |
| 7 | 700 | >580 | | | .155 | | | |

## Table 8

## Predicted Ice Accumulation Due to Drift

| Tower Type | On the Ground | On Structure (1/4 cylindrical Object) |
|---|---|---|
| Natural | <0.001 | <.001 |
| Mechanical | | |
| Standard | 0.2 | 2.6 |
| State-of-the-art | 0.02 | 0.26 |
| Round Mechanical | | |
| Standard | 0.01 | .03 |
| State-of-the-art | <0.001 | <.001 |

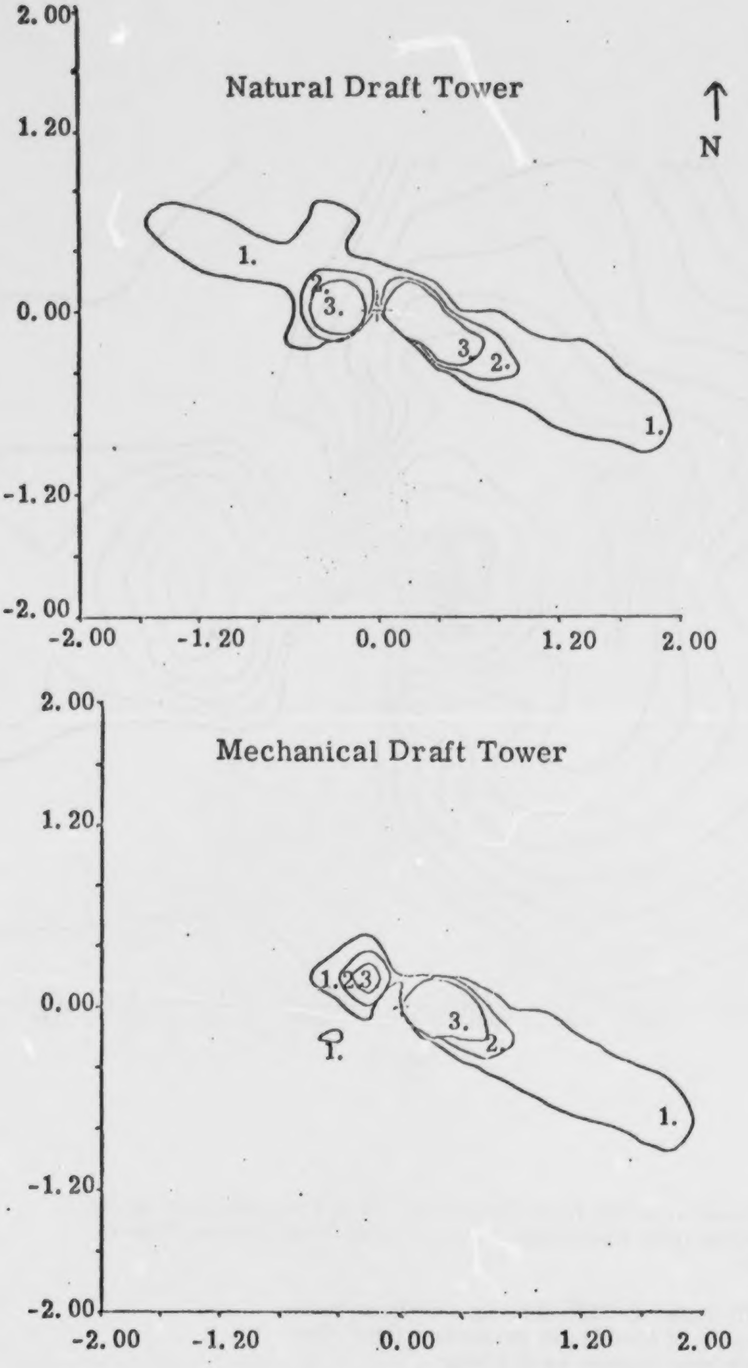


Figure 1

Isopleth of Percent of Possible Sunshine Hours When Shadowing Would Occur During the Month of January

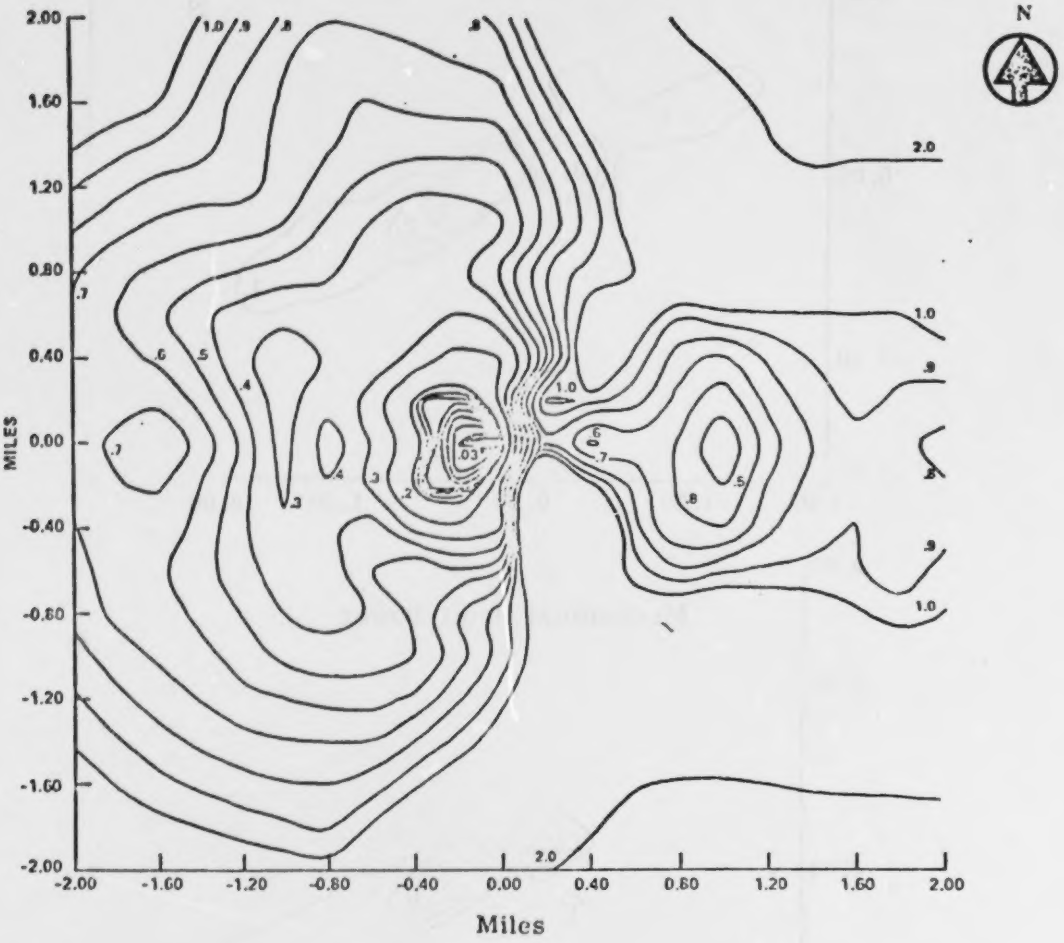


Figure 2

Predicted Annual Average Near Ground Airborne Concentration ($\mu g/m^3$) of Salt Resulting from Operation of One Natural Draft Cooling Tower (0-10 miles)

Basis: Drift Rate: 0.002% (28. Kg salt/hour/tower
Number of towers per generating unit: One
Each hour counted as dry hour
Note: Divide number on plot by 100 to get $\mu g/m^3$

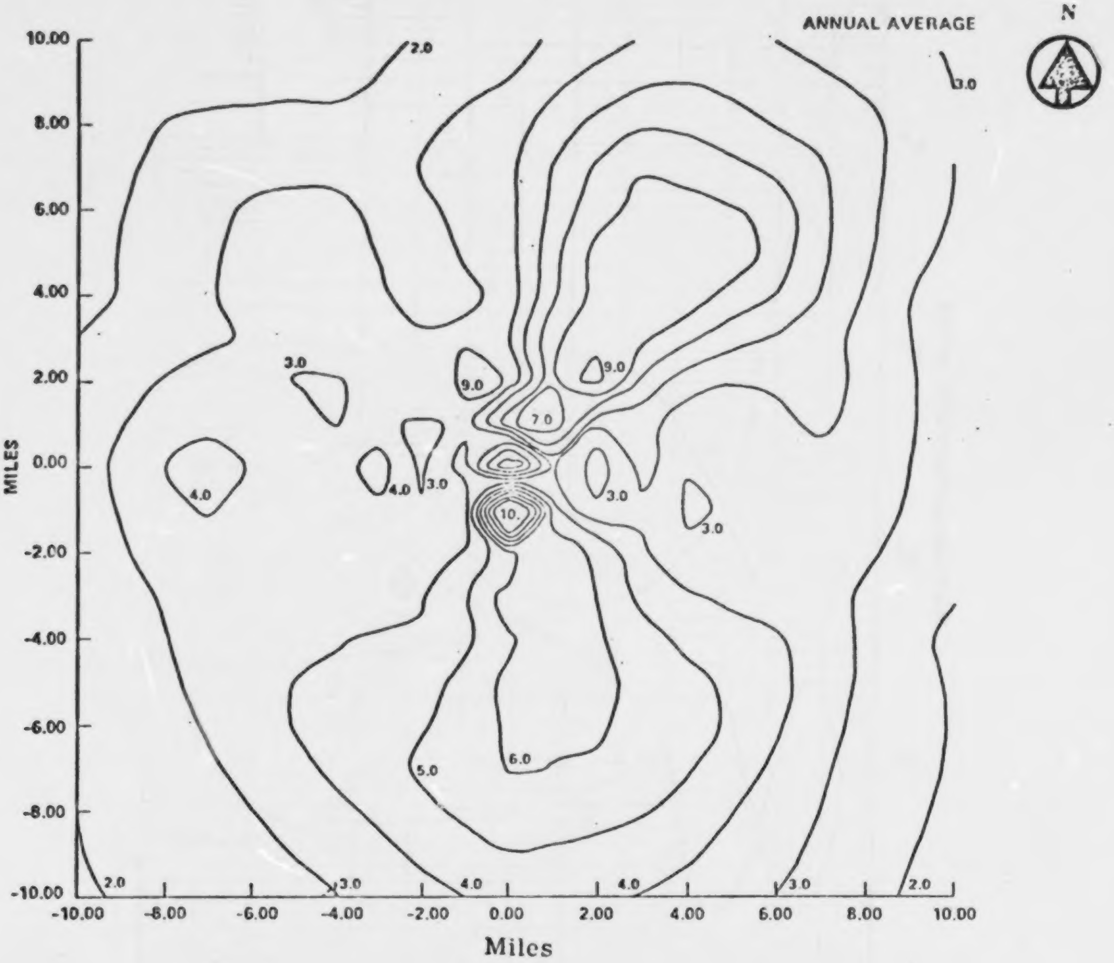

ANNUAL AVERAGE
N
MILES
Miles
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-10.00
-8.00
-6.00
-4.00
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
2.0
3.0
4.0
5.0
6.0
7.0
9.0
10.

Figure 3

Predicted Annual Average Ground Dry Deposition Rate (Kg/Km$^2$-month) of Salt Resulting from Operation of One Natural Draft Cooling Tower (0-10 miles)

Basis: Drift Rate: 0.002% (28. Kg salt/hour/tower)
Number of towers per generating unit: One
Each hour counted as dry hour

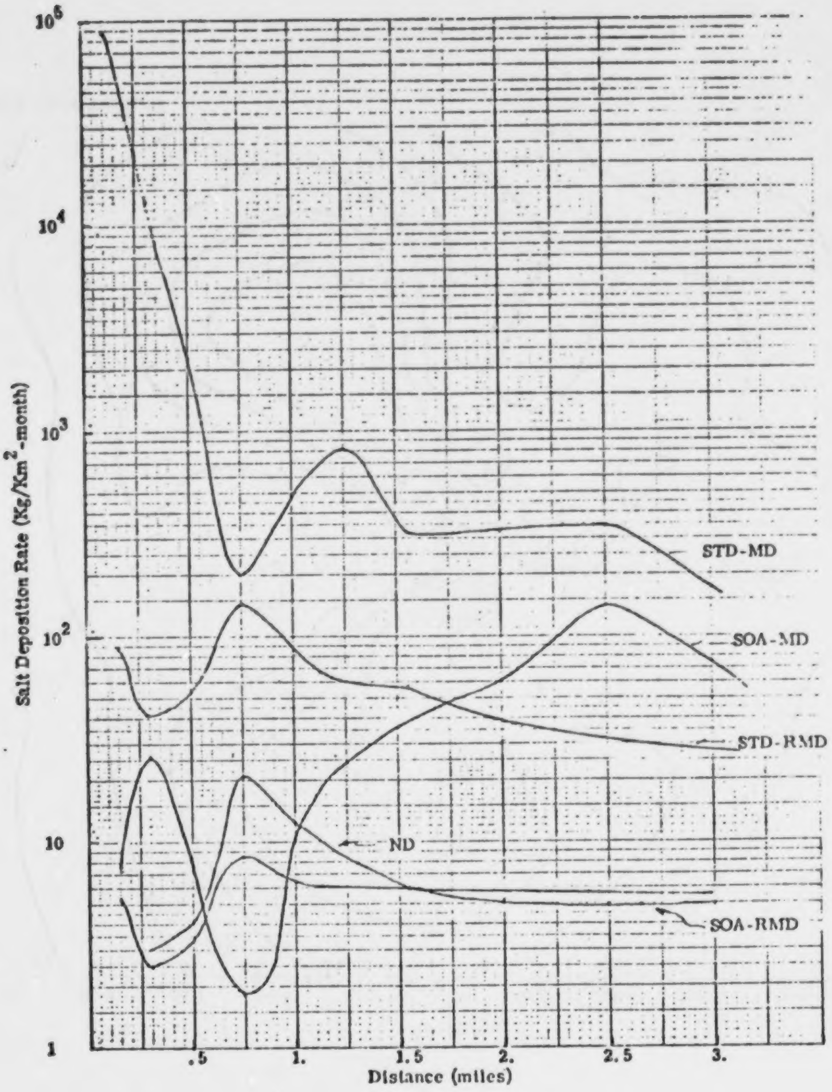


Figure 4

Estimated Annual Average Ground Salt Deposition Rate vs Distance from the Tower in the NE Sector

Basis: One generating unit
Basin salinity: 10,000 ppm
Note: STD = Standard
SOA = State-of-the-Art
ND = Natural draft
MD = Mechanical Draft
RMD = Round mechanical draft

98<
SML

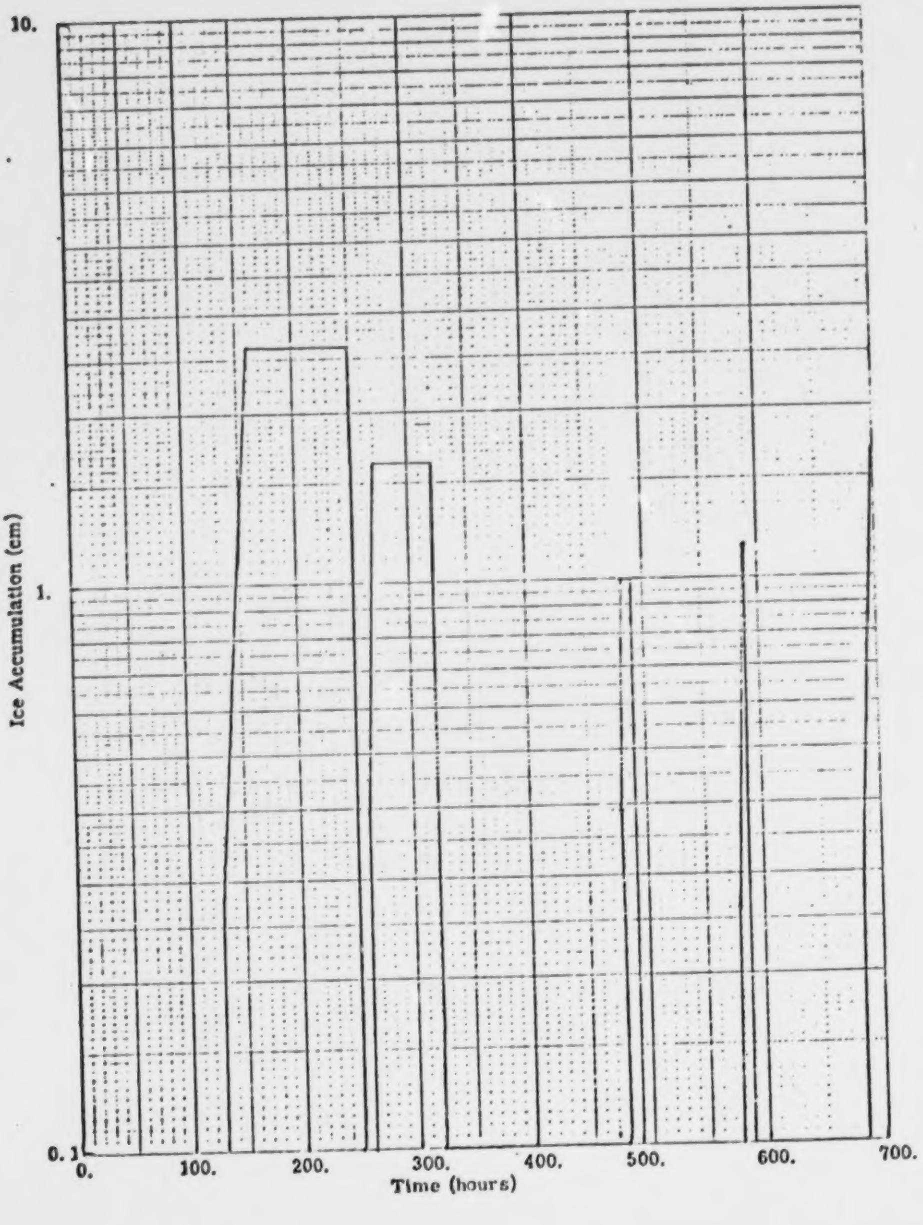


Figure 5

Ice Accumulation on Structures vs Time for the Month of January Due to Operation of Two Standard Mechanical Draft Towers

**Basis:** Drift 0.01% (118.9 Kg salt/hour/unit)
Number of towers per generating unit: Two
Direction: SSE (ice deposits in SSE sector)

**Note:** All values calculated at 250m downwind from the tower
Object type: cylinder - 1/4 inch diameter

39<

6-45-22

# A SYSTEMS APPROACH TO BIOLOGICAL AND THERMAL CONSIDERATIONS IN COOLING LAKE ANALYSES

K. D. Robinson and R. J. Schafish
R. W. Beck and Associates
Denver, Colorado U.S.A.

G. Camougis
New England Research, Inc.
Worcester, Massachusetts U.S.A.

## ABSTRACT

Reliable methodologies to predict the aquatic composition of reservoirs receiving thermal discharge are needed to determine compliance with regulations and could be useful in effective design for utilization of waste heat. A systems approach is described which utilizes state-of-the-art thermal modeling and ecological predictive techniques to evaluate the biological ecocomposition of proposed cooling reservoirs. Focus is on the entire ecosystem dynamics, including major trophic levels. The thermal structure of cooling lakes is discussed based on analytical models. Habitat for individual species is analyzed in terms of lake volume fraction based on transient temperature calculations. Application of the methodology is described and the need for more research is identified.

## INTRODUCTION

The inherent efficiency limitations of nuclear and fossil fuel fired power plants result in large amounts of heat being wasted. The waste (rejected) heat amounts to about 60% to 70% of the total energy released from the fuel source. This waste heat must be conveyed from the power plant to the surrounding environment.

Much concern has developed about the effects of large amounts of heat upon the natural biological systems existing in rivers and lakes used for cooling large power plants. As a result, regulations have been promulgated prohibiting or limiting the use of natural water bodies for such a purpose. These regulations also extend to the creation of an impoundment for cooling as part of an electric generating facility.

In areas of high water consumption and/or relative scarcity of resources, power plants have often included, or been associated with large water supply reservoirs. Such impoundments are frequently multiple-use projects providing irrigation water, municipal water supply, flood control and recreation. In recent years, concern for maintaining minimum flows in streams and rivers has spread to areas where water is less scarce, resulting in adoption of more conservative water-supply policies. Construction of power plants in such areas is more likely to include water supply reservoirs, which will also be attractive for joint use as cooling devices since the incremental cost for use as a cooling reservoir will be significantly lower than that of methods such as cooling towers. Also, such multiple use may result in a savings in water consumption and fuel.

Section 316(a) of the Federal Water Pollution Control Act Amendments of 1972 requires demonstration of a viable aquatic population as a condition for the granting of alternative thermal limitations for cooling reservoirs. Compliance with this and other regulations may require that a proposed cooling lake be analyzed to predict the probable impacts of thermal loading upon the biota expected to exist in it. Such analysis can provide insight into the ecological relationships among the major trophic levels in a cooling lake and the effects of thermal effluents upon those relationships and upon individual species within each level. Many regulations are only fragmentary in their consideration of the true ecological implications of what they attempt to regulate, and an analysis which is responsive to regulatory requirements may be seriously deficient from an ecological viewpoint. Therefore, an analysis going beyond the regulatory requirements to establish the basic components of a biological system and thoroughly assess that system may be appropriate.

Proper lake management is in the best interests of both the lake ecosystem and efficient power plant generation, as undesirable biological developments can cause a variety of operational problems. Reliable predictive methodologies can minimize such problems. It is probable that such predictive techniques can increase the effectiveness of designs for utilization of waste heat to enhance the productivity of selected biological species.

## A SYSTEMS APPROACH

The major components of a cooling lake which will influence the development of the biological system are:

(1) physical characteristics of the lake
(2) water quality
(3) thermal input, both natural and induced

These major components determine the characteristics of the habitat which will exist within the lake. The biota also will exert great influence upon the lake characteristics, and the entire system will undergo constant change.

The methodology discussed herein was developed in the context of a 316(a) Demonstration Study for a cooling lake for a proposed electric generating station. However, it can be utilized as an evaluative tool for other purposes as well. The intent of this paper is to present a qualitative description of the methodology. The generalized systems approach to cooling lake analysis is shown schematically in Figure 1.

Evaluation of an aquatic ecosystem will be based upon the conventional components used to describe any ecosystem; consequently, both the biotic and abiotic factors become critical. If the aquatic system is already in existence, then it is necessary to describe that system in appropriate detail. If the system is proposed but not in actual existence, it is necessary to predict the ecosystem that will exist in the proposed water resource. Criteria for multiple-use objectives can then be applied in order to optimize the system and define the appropriate lake management scheme to achieve those objectives. The inputs to the evaluation include the following:

(1) ecosystem theory (based on known limnological phenomena)
(2) the physical features of the proposed lake
(3) the probable water quality of the proposed lake
(4) the thermal structure of the lake
(5) actual field experience with similar lakes of geographic proximity.

In order to adequately evaluate the response of a reservoir biosystem to elevated temperatures, a detailed description of the thermal environment, including variations over time, is necessary. Early mathematical models for cooling lake analysis have been relatively simple empirical formulations which were used to ensure proper lake sizing for plant design and heat transfer purposes. Predicted temperatures were usually spatial and temporal averages and were not adequate for satisfactory biological projections. Recently, however, model development has progressed to the state where transient thermal and hydrodynamic descriptions of cooling lakes can be made which will allow biologists to make refined predictions of the biota of cooling lake ecosystems. Such information can be used to determine compliance with regulations, to identify potential problems in lake operation and, perhaps, even to allow the design of commercial aquaculture systems.

## COOLING RESERVOIR DESCRIPTION

The physical-chemical state of a cooling reservoir is a function of many variables, including geographic location, morphometry and meteorology. Plant size and operating characteristics, as well as intake and discharge location and design are other important variables. Two of the more significant parameters in evaluating cooling reservoir ecosystems are temperature and dissolved oxygen (D.O.). Natural lakes and reservoirs undergo seasonal changes such as summer heating and stratification, stagnation with accompanying D.O. depletion, overturn, fall cooling and, possibly, winter freezing. Thermal discharge from power plants can significantly alter these cyclical conditions and the attendant biological activity.

### Natural Reservoir

Natural reservoir models predict variations in the thermal structure of proposed impoundments. These models utilize lake geometry and suitable averages for meteorological variables to predict vertical temperature profiles for specified time intervals. For these studies, a natural reservoir model developed at the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics at the Massachusetts Institute of Technology (M.I.T.) was used[1]. Other models available include analyses developed by Cornell University and by Water Resource Engineers (WRE). An interesting evaluation of these models was made by Parker, et al.[2] at Vanderbilt University.

## Thermal Discharge

Studies made at the Ralph M. Parsons Laboratory have shown that, with proper design, cooling water discharge from a power plant will form a distinct heated surface layer (due to density differences) which will remain intact and tend to spread over the entire surface of the reservoir. This can produce a stratified condition over an entire year of operation and is especially desirable since heat transfer is a direct function of surface temperature. Any dilution of the discharge (e.g. by improper discharge design and location) will lower the surface temperature and thus reduce the net heat transfer to the atmosphere. In addition, if plant intake water is withdrawn from the cooler sub-layers of the reservoir, the stratified condition provides thermal inertia (that is, slower response to short-term meteorological fluctuations).

Ryan and Harleman[3] have developed a mathematical model for an idealized cooling pond which separates the water body into a discharge mixing region, a warm surface layer and a cooler sublayer (Figure 2). Heated discharge water enters the surface layer, where it entrains cooler subsurface water and then flows to the far end of the reservoir, effecting a plug flow type of heat transfer to the atmosphere. Considerable research on surface heat transfer mechanisms conducted by M.I.T. provides state-of-the-art thermal analysis. At the end of the surface layer, destratification causes downwelling mass transfer to the sublayer. Heat transfer to the sublayer occurs through this downwelling connection as well as by solar radiation not absorbed by the surface layer. The sublayer can be assumed at constant temperature or vertically stratified.

A dimensionless parameter called the "Pond Number" ( $\mathbb{P}$ ) has also been developed at M.I.T.[4]. It is the ratio of the surface layer thickness ($h_s$) to the average depth of the reservoir ($H_s$). The Pond Number indicates whether a cooling reservoir will be strongly or weakly stratified. Since thermal stratification, to some extent, defines biological habitat, it is useful to note the important variables in the expression for $\mathbb{P}$ : discharge volume, condenser temperature rise and lake geometry (length/width$^2$). The greater the discharge volume, the thicker the surface layer (larger $\mathbb{P}$ ). Alternatively, a higher condenser temperature rise results in a thinner surface layer (smaller $\mathbb{P}$ ).

The shape of the lake has a substantial influence on ($h_s$) and, therefore, $\mathbb{P}$ . A long, narrow lake, will have a thicker surface layer than a wider, more nearly round reservoir for given plant operation conditions. For example, a 1000 MW plant discharging into the two dissimilar reservoirs shown in Figure

3 will create distinctly different surface layers ($h_s$ = 8 ft for narrow lake; $h_s$ = 3 ft for wide lake).

The cooling pond model described above has been incorporated into a computer program by M.I.T. which generates transient reservoir temperatures for given lake geometry, meteorological parameters and plant operating characteristics. Figure 4 demonstrates vertical temperature profiles from the natural and cooling reservoir models. Figure 5 shows typical predicted surface temperatures for a given day based on 24-hour averages of meteorological data. Also shown in the insets are expected natural reservoir and cooling lake temperature profiles for representative lake locations.

Studies have shown that, contrary to popular belief, most of a lake surface is effective for heat transfer, including that of long side arms.[5] Density differences cause buoyancy-driven circulation in these side arms and effect significant cooling. Warm surface water (less dense) enters the side arm and cools as it flows toward the end where destratification causes downwelling. The water then returns to the main body of the reservoir through the side arm sublayer. Calculations show temperature variations along a side arm of up to 5 F. This type of analysis allows extrapolation of model predictions to detailed lake geometry (as shown in Figure 5).

Both horizontal and vertical isotherms are important considerations in predicting the distribution of particular species within the reservoir at given times of the year. In particular, peak summer temperatures as well as minimum winter temperatures are significant in considering upper and lower avoidance ranges. Artificially introduced species such as the threadfin shad will be especially sensitive to wintertime conditions. Likewise, some fish will tend to avoid areas with elevated temperatures in the summer.

Since available habitat for various species is an important consideration in the ecosystem evaluation, a useful method of interpreting the temperature predictions is by lake volume fraction. This technique shows what percent of the lake volume is above or below given temperature ranges at any specific time. Figure 6 shows the temperature and lake volume fraction variation with depth for a given day. Figure 7 shows a temperature vs. volume fraction plot for both thermal discharge and natural reservoir conditions. This approach allows a quantitative definition of available thermal habitat for particular species and can indicate the potential effect of the thermal discharge. A similar habitat definition with respect to D.O. might be valuable.

A time-integrated interpretation of volume fraction is demonstrated qualitatively in Figure 8. The curves indicate an upper (or lower) bound for temperature. At any given date, the percent of total habitat below a specific temperature can be identified.

Plant operating characteristics can have a significant effect on the thermal response of a reservoir. At a fixed heat discharge, condenser temperature rise will vary with condenser flow rate. Because net heat transfer from the lake to the atmosphere is a direct function of surface temperature, a higher condenser $\Delta$ T will result in more efficient cooling and less thermal impact on the lake for a given heat rejection rate. Figure 9 shows this effect for condenser temperature rises of 20 F and 27.5 F. Sublayer temperatures can vary by as much as 2 F. This type of analysis can be used to optimize plant operation and design according to stated objectives.

### Enhanced Mixing

One benefit of cooling water discharge which has been observed in operational cooling lakes (for example, Lakes Sangchris and Baldwin) is a reduction of the D.O. depletion which occurs in natural reservoirs in the summer. The hydrodynamics of properly designed cooling reservoirs (with typical residence times of 8 to 15 days) allow a lake to "breathe." Substantial water mass transfer from the aerated surface layer to the sublayer enhances the D.O. in the normally stagnant lower depths. This has significant implications in ecosystem dynamics.

## APPLICATION OF ECOSYSTEM THEORY

The results of the thermal models provide powerful tools to examine the thermal structure of a future cooling lake in the context of ecosystem theory. Important features described above include:

(1) horizontal isotherms,
(2) vertical stratifications, and
(3) volume fractions within specified isotherms.

Information about these features allows for evaluation of the probable effects of the thermal discharge on the lake ecosystem. All trophic levels, including (1) bacteria, (2) algae, (3) macrophytes, (4) benthic organisms, (5) zooplankton and (6) fish species, can be evaluated. This approach puts the emphasis on the total system and not just on certain species. It is interesting to note that Coutant(6) in a recent article mentioned that the environmental assessment process has matured and is moving in this direction. Figure 10 presents a simplified diagram of an aquatic ecosystem, including both grazing and detritus food chains. Interrelationships of system components, as well as responses of individual components, determine total system response to changes such as elevated temperatures.

It is well known that temperature is an important parameter in the productivity of aquatic species, and that each species has an optimum temperature. Temperature predictions can be applied to such relationships to evaluate the effect of thermal discharge on particular species. Figure 11, which illustrates the quantitative variation of species productivity with temperature shows an increase in productivity when a natural reservoir is utilized as a cooling lake. Obviously, productivity will decrease when temperature is elevated beyond a certain point.

Within given trophic levels, thermal tolerance will vary among species. Fish populations are useful to illustrate this point. Figure 12 demon-

105<

strates the effect of temperature on the probability of survival of fish populations. An increase in lake temperatures will alter the populations to favor the more thermally tolerant species. It is worthwhile to note that, because thermal tolerance varies within any given species, as described by Gibbons[7], absolute temperature threshholds derived in the laboratory may be inappropriate criteria for prediction of responses to temperature in biological populations under actual field conditions. Maintenance of elevated temperatures may favor propagation of those individuals with higher thermal tolerance.

An example of a shift in biological community composition resulting from temperature elevation is shown in Figure 13. Algal populations will shift from the diatoms to the green to the bluegreen algae with elevation in temperature. Similar analysis can be made for other trophic levels and then integrated to evaluate the effect on the total ecosystem in addition to that on certain species.

## PRACTICAL APPLICATION

Description of the ecosystem that is expected to develop in the cooling lake is the last step in the predictive process. Subsequent use of the results of the technique must take into account the reason for performing the analysis in the first place. One important reason is the regulatory requirement to perform a study in order to use a lake for cooling purposes. Once the analytic work has been completed, this factor comes into play in determining how the results of the study are used. The study results must be compared with the regulatory standards to determine whether the basic concept is acceptable. Once this is determined, the objectives of regulatory agencies and of the cooling lake proponent must be reconciled where they conflict.

Meeting regulatory requirements does not preclude the possibility of problems or nuisances such as prolific growth of aquatic weeds and algae. Occurrence of such problems can be predicted with reasonable accuracy using the results of the ecosystem analysis, and a strategy for control can be developed. A more difficult problem results when the fish population of the reservoir is considered. The language of Section 316(a) refers to a "balanced indigenous population". However, the fish populations that may satisfy the letter of the law may not be considered the most desirable by State or Federal agencies. Many states consider the waters of an impoundment as "waters of the State" and view them as an important resource to be managed for public use and benefit. They may require that the lake fishery be managed to produce a maximum yield of sport fish such as largemouth bass. Such use of the lake need not conflict with the objectives of the utility sponsoring the project. A public facility which is an asset to the region is a benefit from the perspective of gaining public acceptance and support for the project.

Conflicts may exist, however, if the cost of lake management is close to that of off-stream cooling. Then that alternative may become more attractive to the utility, expecially when liability is also considered. Development of a management plan for the cooling lake must include the identification of problems that are expected to occur along with delineation of the objectives of the program from the viewpoints of both the regulatory agency and the utility. The management program may include control of weeds and algae, erosion control, vegetation of shoreline, selective stocking of sport fish and recreation development.

## NEED FOR ADDITIONAL WORK

Use of predictive modeling techniques relies upon the accuracy and reliability of the models themselves. The components that define a cooling lake ecosystem may be categorized under three general headings. These are temperature, water quality and biology. The first is probably the most advanced due to the efforts which have been expended and the nature of the problem, which makes it more amenable to analysis. The latter two are more closely interrelated and more difficult to analyze.

Dissolved oxygen and nutrient mass balance are important factors in water quality. Oxygen is a determinant of habitat in much the same way as temperature, and it appears that the concept of describing the lake volume in terms of dissolved oxygen level may be of use. However, much work needs to be done to advance the state of the art in predicting dissolved oxygen levels in lakes and reservoirs. Definition of the effect of different oxygen levels on behavior of fish and other organisms also needs additional investigation.

Much the same can be said of the capability to predict biological interaction, which is an even more complex area than thermal effects and water quality. Study of cooling lakes may afford a unique opportunity to analyze the development and interaction of lake ecosystems, since these facilities are relatively small compared to other major water supply projects, and they are often the subject of permit conditions which require water quality, thermal and biological monitoring. Currently, there is active interest in the development of predictive biological models. Further progress in the integration of various parameters, as proposed in this paper, will allow the development of an extremely powerful predictive tool with multiple uses and applications.

## REFERENCES

1. Ryan, P.J., and Harleman, D.R.F. 1971. "Prediction of the Annual Cycle of Temperature Changes in a Stratified Lake or Reservoir: Mathematical Model and User's Manual". Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics Report No. 137. Cambridge: The Massachusetts Institute of Technology.

2. Parker, F.L.; Benedict, B.A.; and Tsai, C. 1975. "Evaluation of Mathematical Models for Temperature Prediction in Deep Reservoirs". National Environmental Research Center, Office of Research and Development, U.S. EPA - 660/3-75-038.

3. Ryan, P.J., and Harleman, D.R.F. 1973. "An Analytical and Experimental Study of Transient Cooling Pond Behavior." Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics Report No. 161. Cambridge: The Massachusetts Institute of Technology.

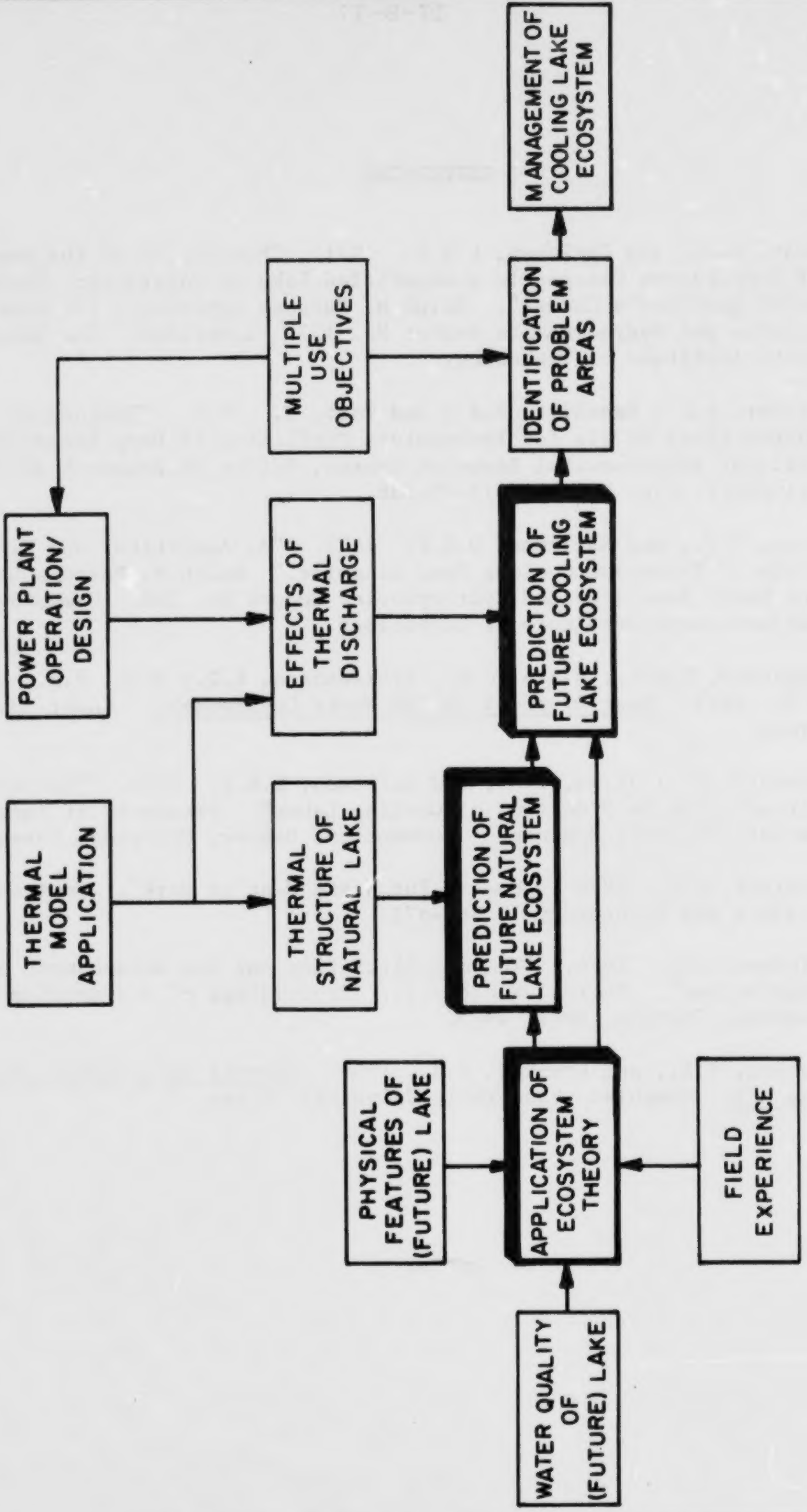
4. Harleman, D.R.F.; Jirka, G.H.; Stolzenback, K.D.; Ryan, P.J.; and Adams, E.E. 1977. Heat Disposal in the Water Environment. Cambridge: M.I.T. Press.

5. Brocard, P. ; Jirka, G.H.; and Harleman, D.R.F. 1975. "Buoyance-Driven Circulations in Side Arms of Cooling Lakes". Presented at American Society of Civil Engineers' Convention, Denver, Colorado, November, 1975.

6. Coutant, C.C. 1976. "How to Put Waste Heat to Work". Environmental Science and Technology 10:868-871.

7. Gibbons, J.W. 1976. "Thermal Alteration and the Enhancement of Species Populations". Thermal Ecology II. Proceedings of a symposium held at Augusta, Georgia, April 1975.

8. Parker, F.L., and Krenkel, P.A. 1969. Thermal Pollutions: Status of the Art. Memphis: Vanderbilt University Press.

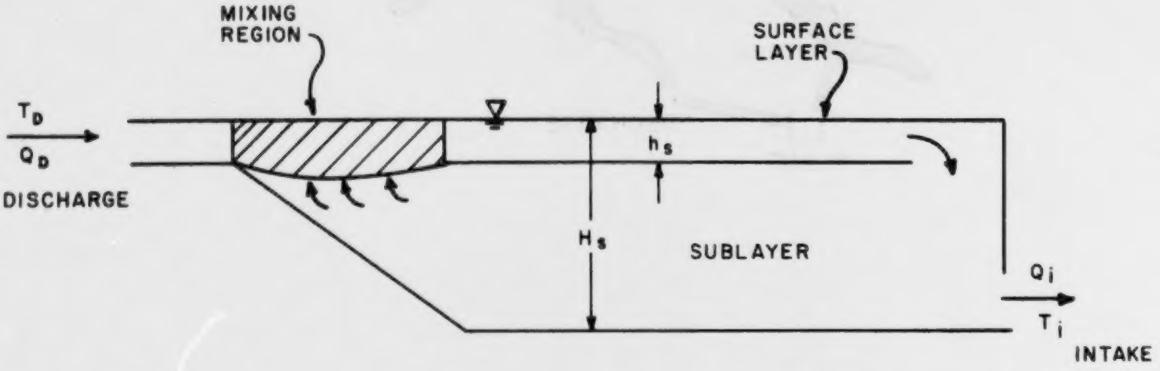

WATER QUALITY OF (FUTURE) LAKE
PHYSICAL FEATURES OF (FUTURE) LAKE
APPLICATION OF ECOSYSTEM THEORY
FIELD EXPERIENCE
PREDICTION OF FUTURE NATURAL LAKE ECOSYSTEM
THERMAL MODEL APPLICATION
THERMAL STRUCTURE OF NATURAL LAKE
POWER PLANT OPERATION/ DESIGN
EFFECTS OF THERMAL DISCHARGE
MULTIPLE USE OBJECTIVES
PREDICTION OF FUTURE COOLING LAKE ECOSYSTEM
IDENTIFICATION OF PROBLEM AREAS
MANAGEMENT OF COOLING LAKE ECOSYSTEM

109<

10

SCHEMATIC DIAGRAM OF A SYSTEMS APPROACH
TO PREDICTION OF COOLING LAKES ECOSYSTEM

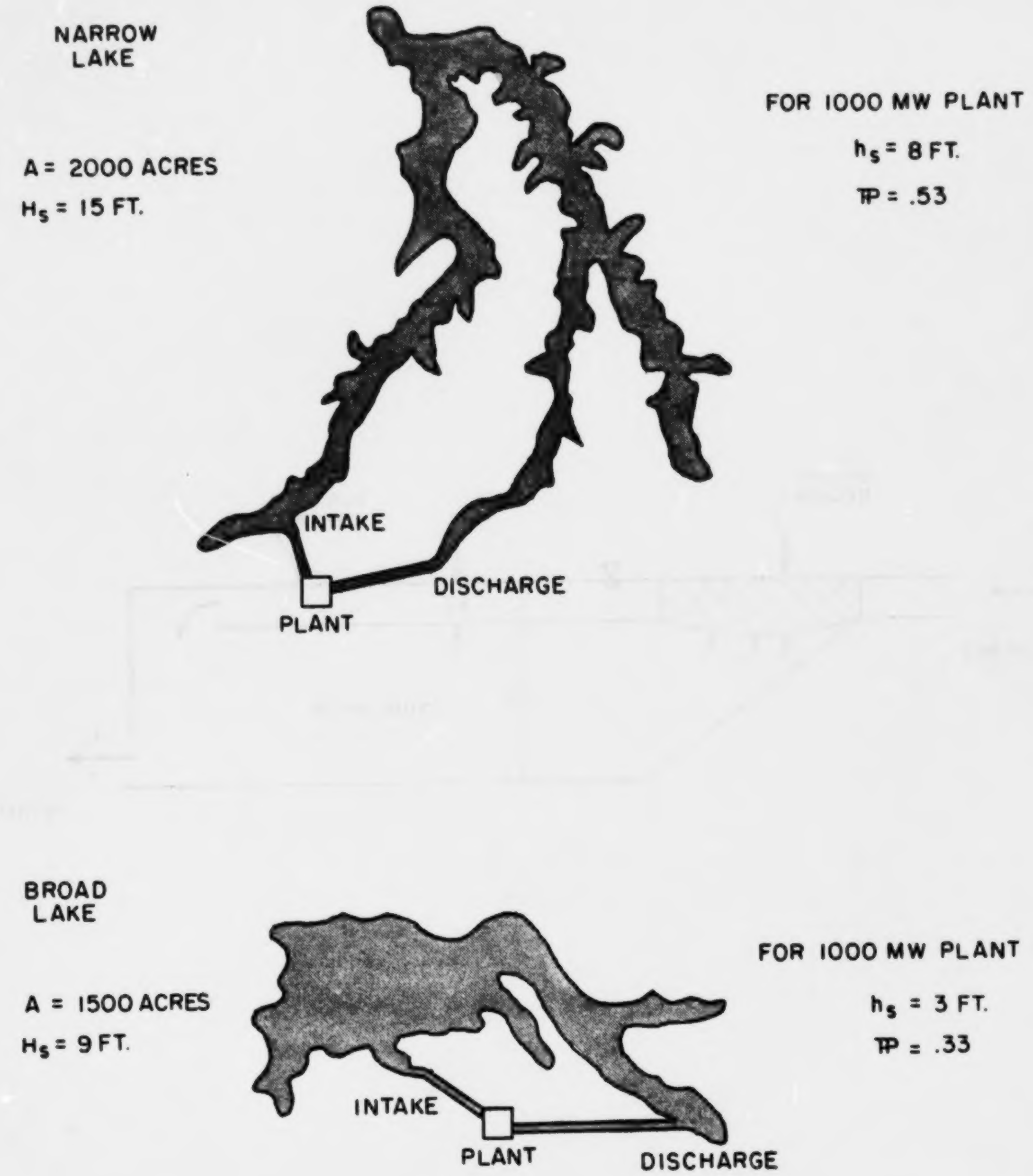
FIGURE I


MIXING REGION
SURFACE LAYER
$T_D$
$Q_D$
DISCHARGE
$h_s$
$H_s$
SUBLAYER
$Q_i$
$T_i$
INTAKE

110<

IDEALIZED COOLING POND MODEL

FIGURE 2 //

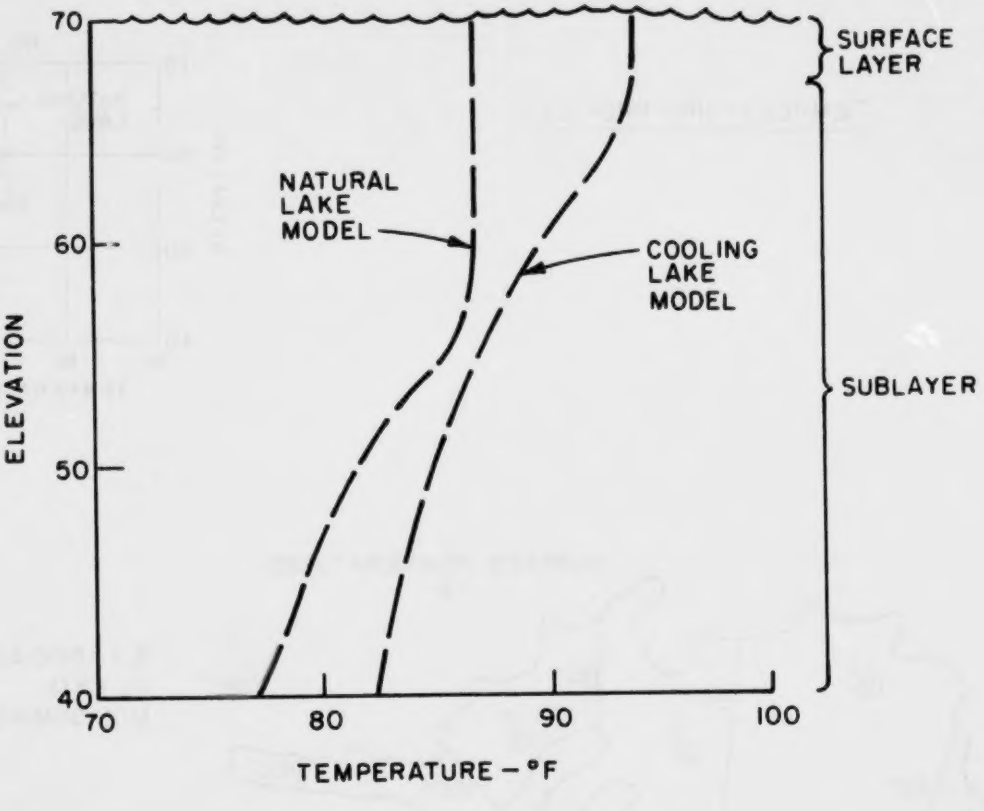

NARROW LAKE
A = 2000 ACRES
$H_s$ = 15 FT.
FOR 1000 MW PLANT
$h_s$ = 8 FT.
TP = .53
INTAKE
DISCHARGE
PLANT
BROAD LAKE
A = 1500 ACRES
$H_s$ = 9 FT.
FOR 1000 MW PLANT
$h_s$ = 3 FT.
TP = .33
INTAKE
PLANT
DISCHARGE

111<

COMPARISON OF SURFACE LAYER THICKNESS
FOR TWO DIFFERENT TYPES OF COOLING LAKES

FIGURE 3

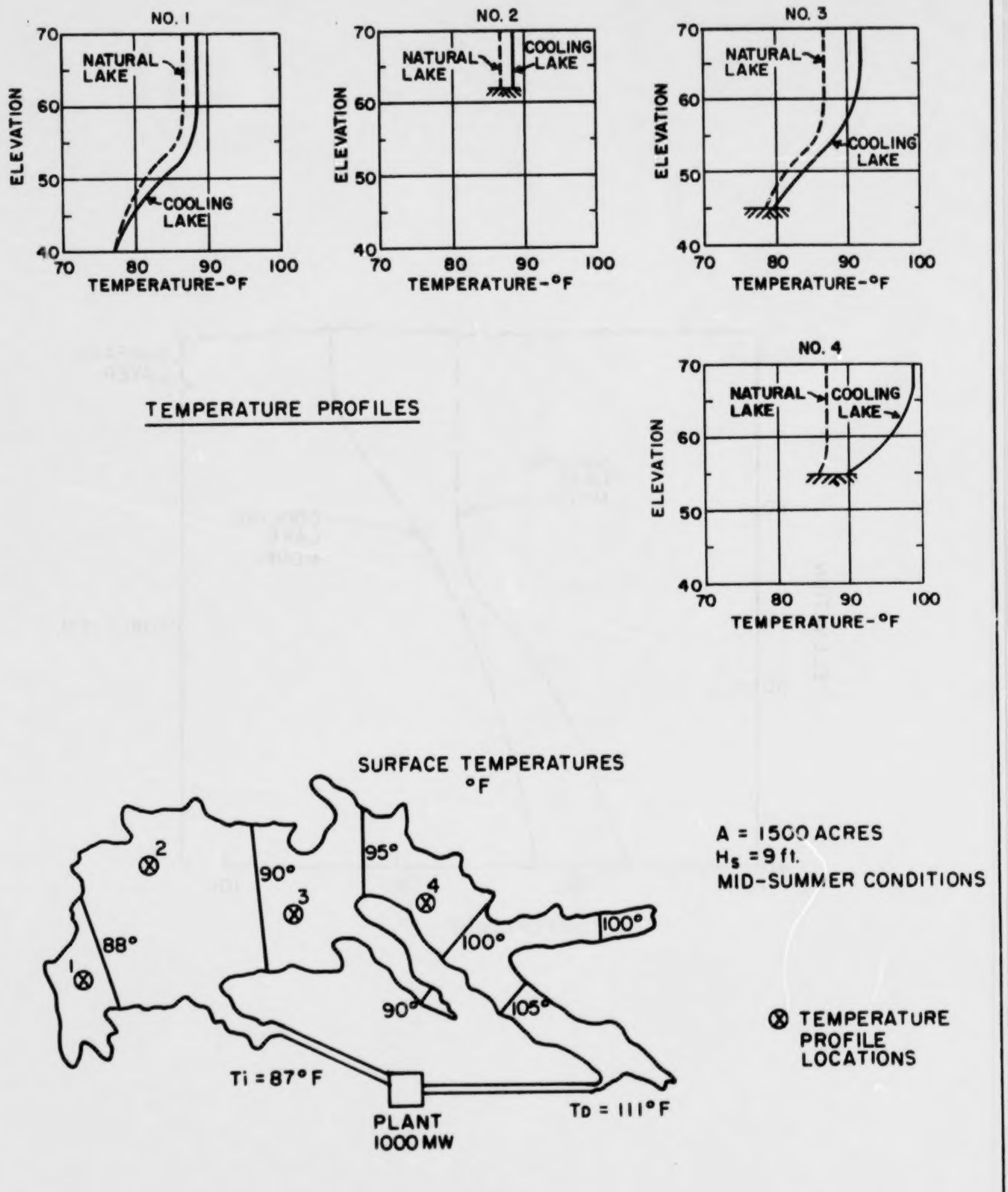
12



112<

COMPARISON OF TYPICAL TEMPERATURE PREDICTIONS
FOR NATURAL LAKE AND COOLING LAKE
MID-SUMMER CONDITIONS

FIGURE 4 13

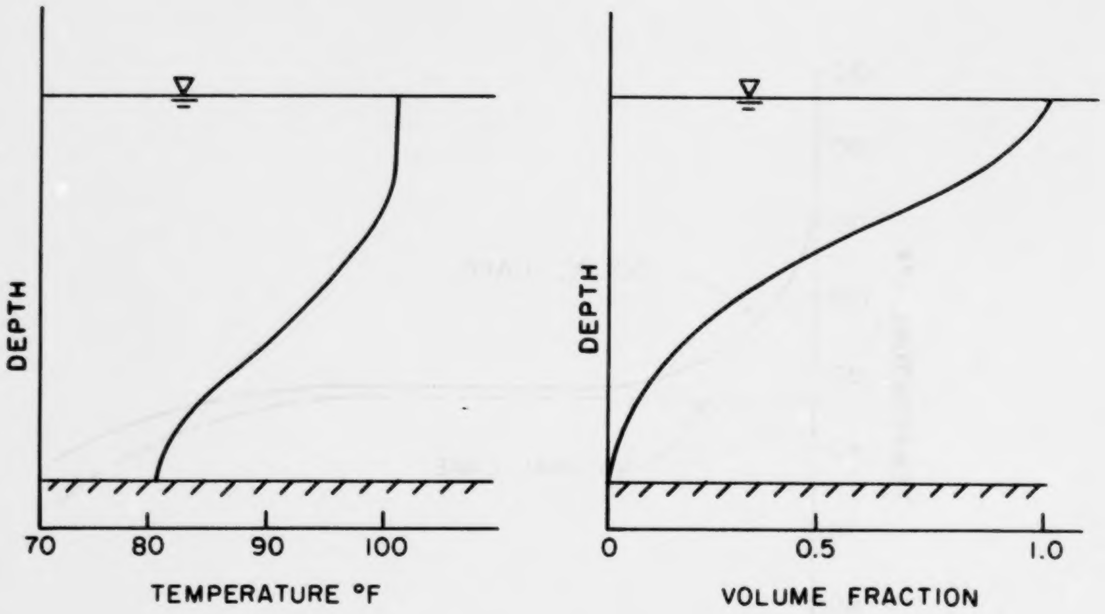


113<

14

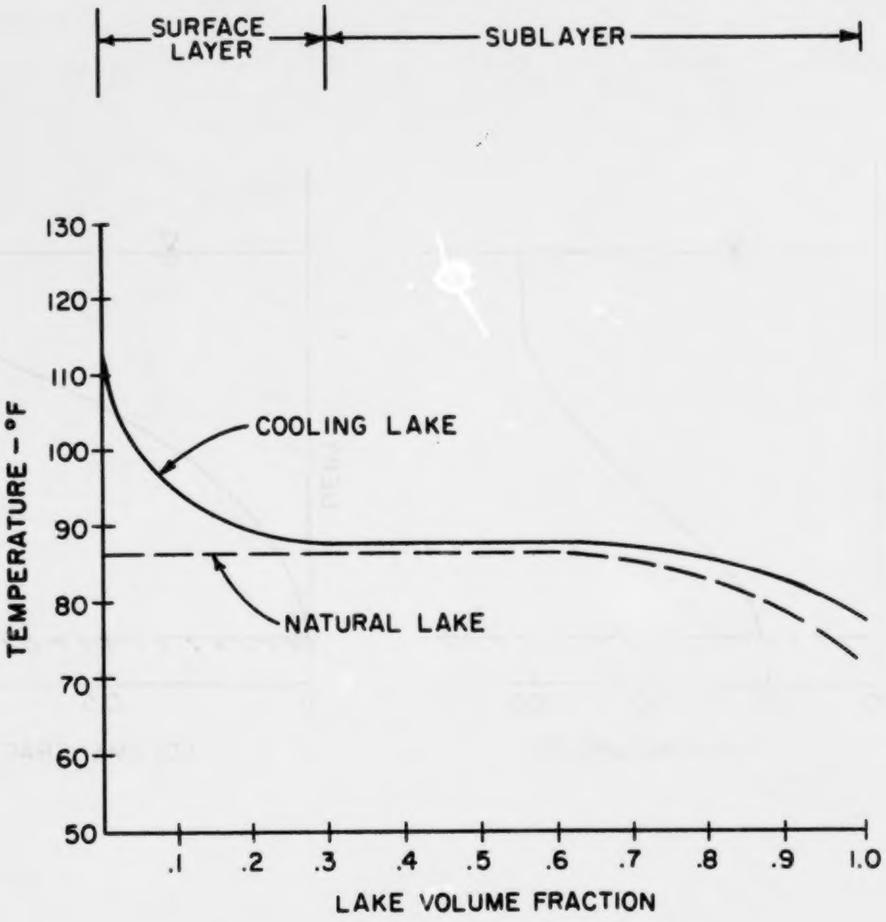
TEMPERATURE DISTRIBUTION AND PROFILES

FIGURE 5



VARIATION OF TEMPERATURE AND VOLUME FRACTION WITH DEPTH

FIGURE 6

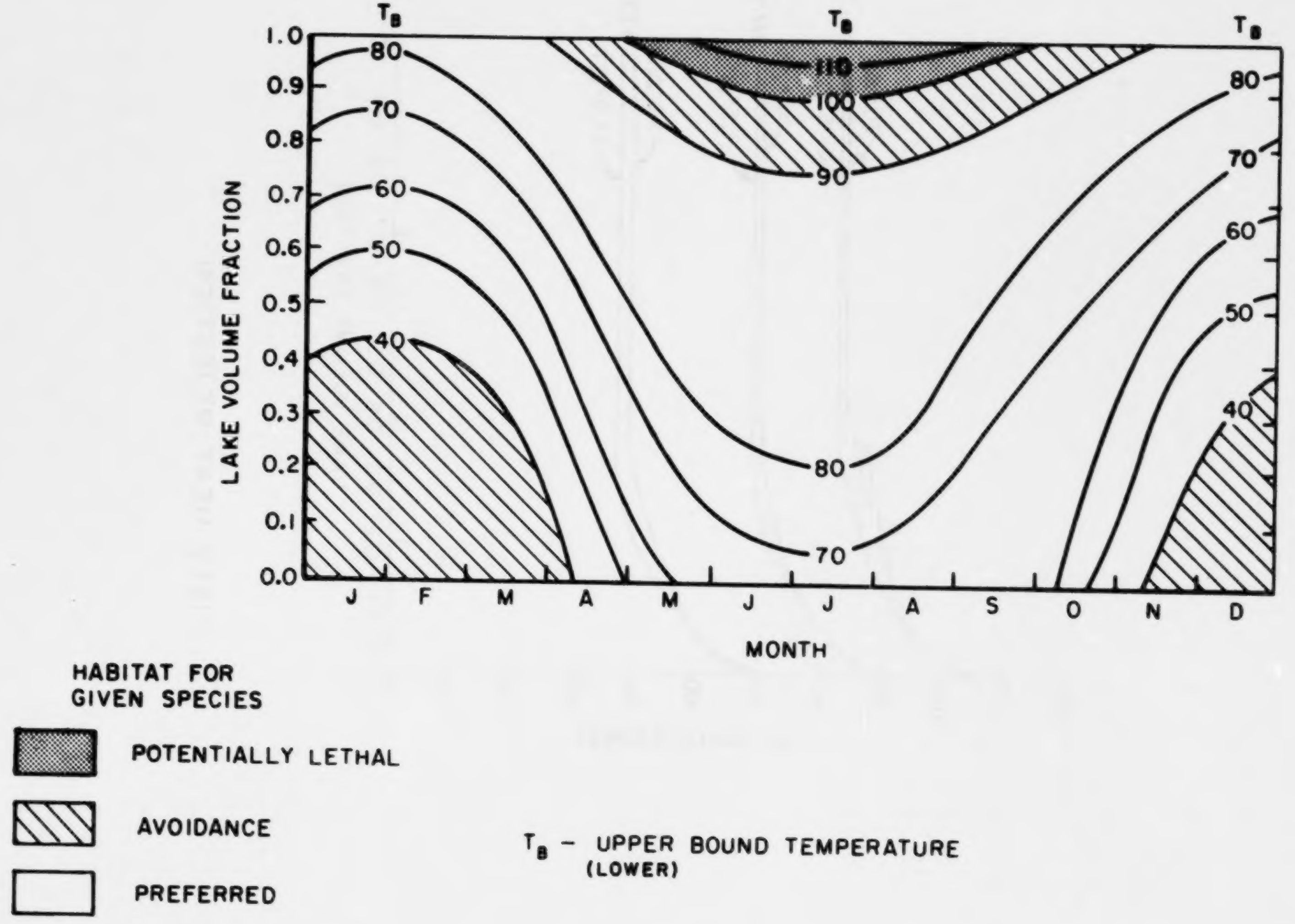


115<

16

TEMPERATURE DISTRIBUTION VS LAKE VOLUME FRACTION

FIGURE 7

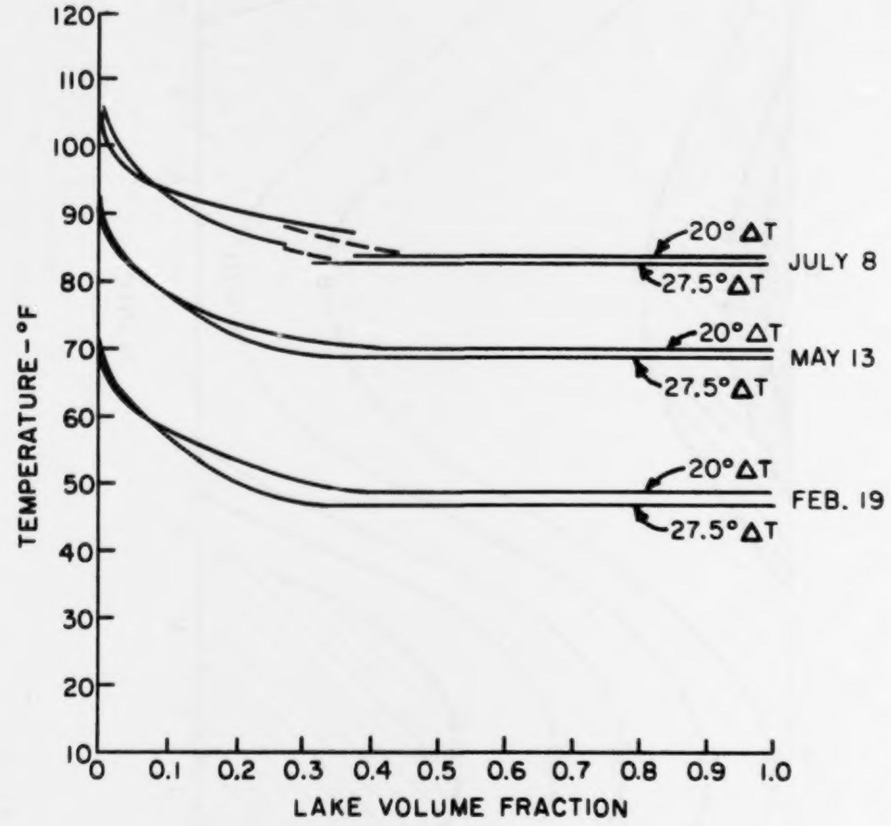


HABITAT DEFINITION
LAKE VOLUME FRACTION vs TIME
FOR UPPER BOUND TEMPERATURES

FIGURE 8

116<

17



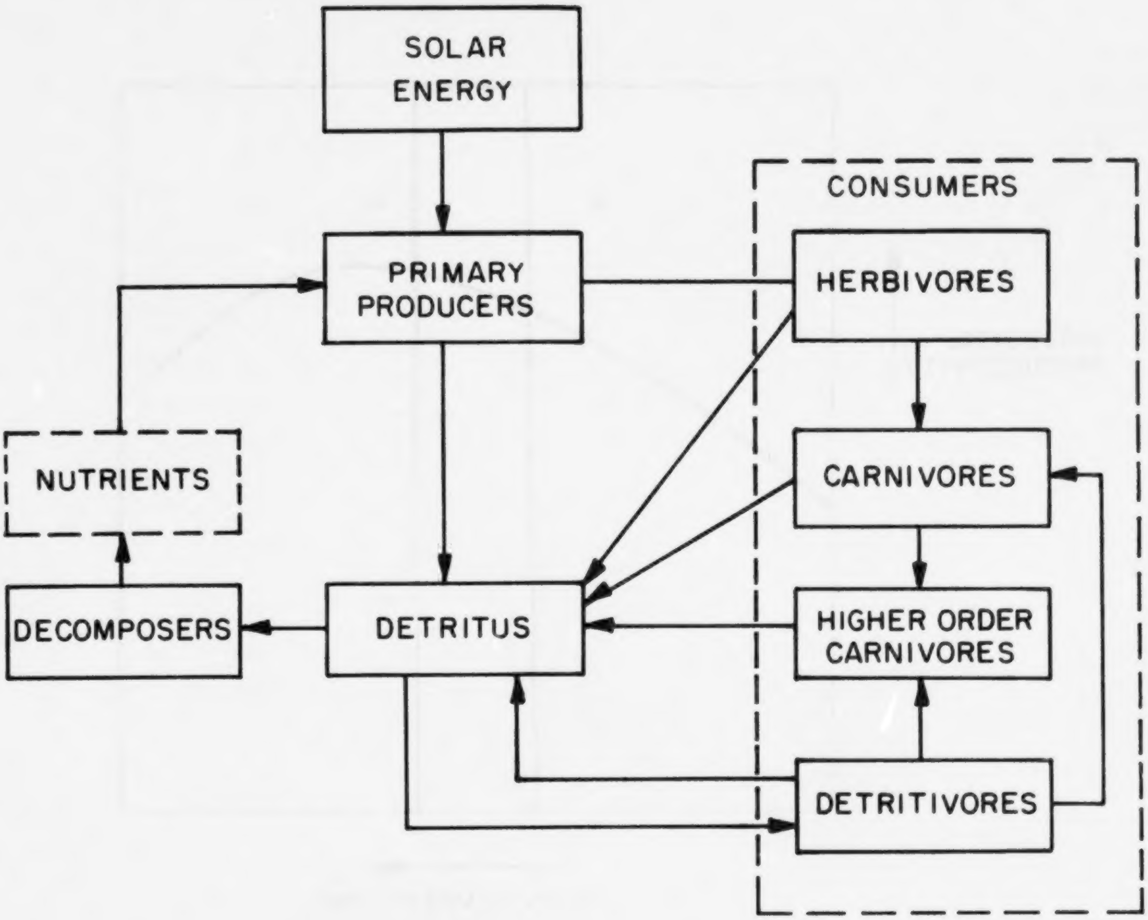
FIXED HEAT REJECTION

117<

18

COMPARISON OF TEMPERATURE – VOLUME FRACTION DISTRIBUTION FOR CONDENSER TEMPERATURE RISE OF 20°F AND 27.5°F

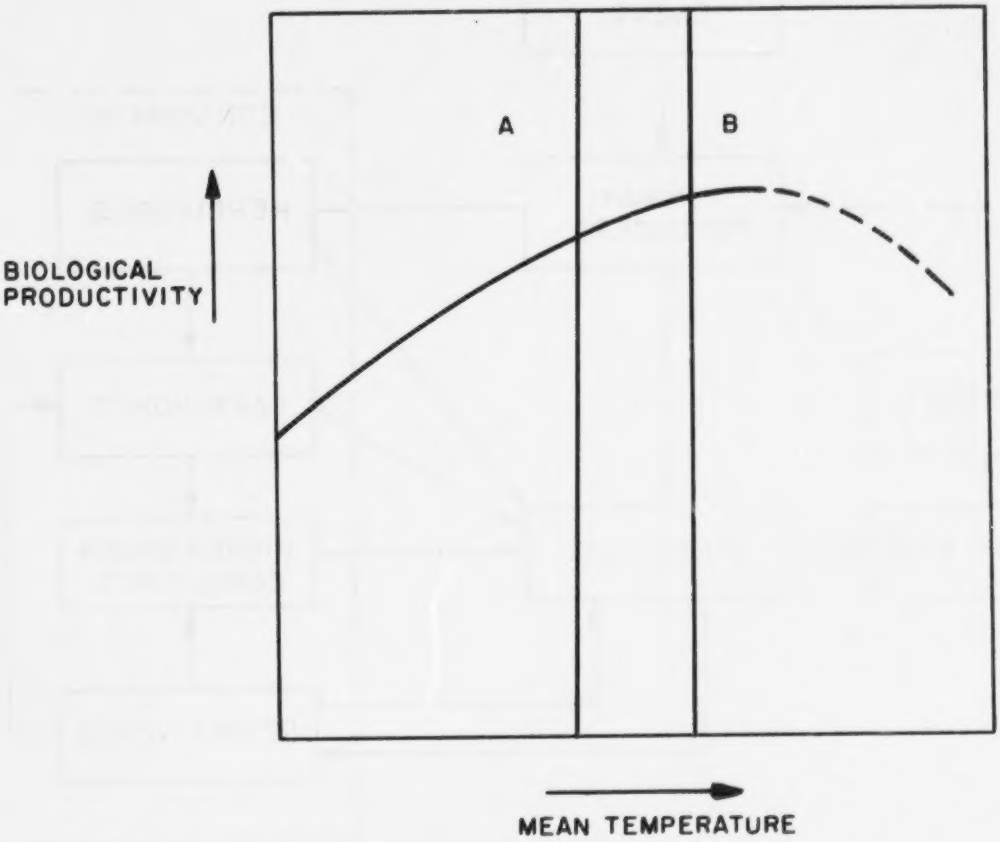
FIGURE 9


SOLAR ENERGY
CONSUMERS
PRIMARY PRODUCERS
HERBIVORES
NUTRIENTS
CARNIVORES
DECOMPOSERS
DETRITUS
HIGHER ORDER CARNIVORES
DETRITIVORES

118<

SIMPLE DIAGRAM OF AN AQUATIC ECOSYSTEM INDICATING BOTH GRAZING AND DETRITUS FOOD CHAINS

FIGURE 10



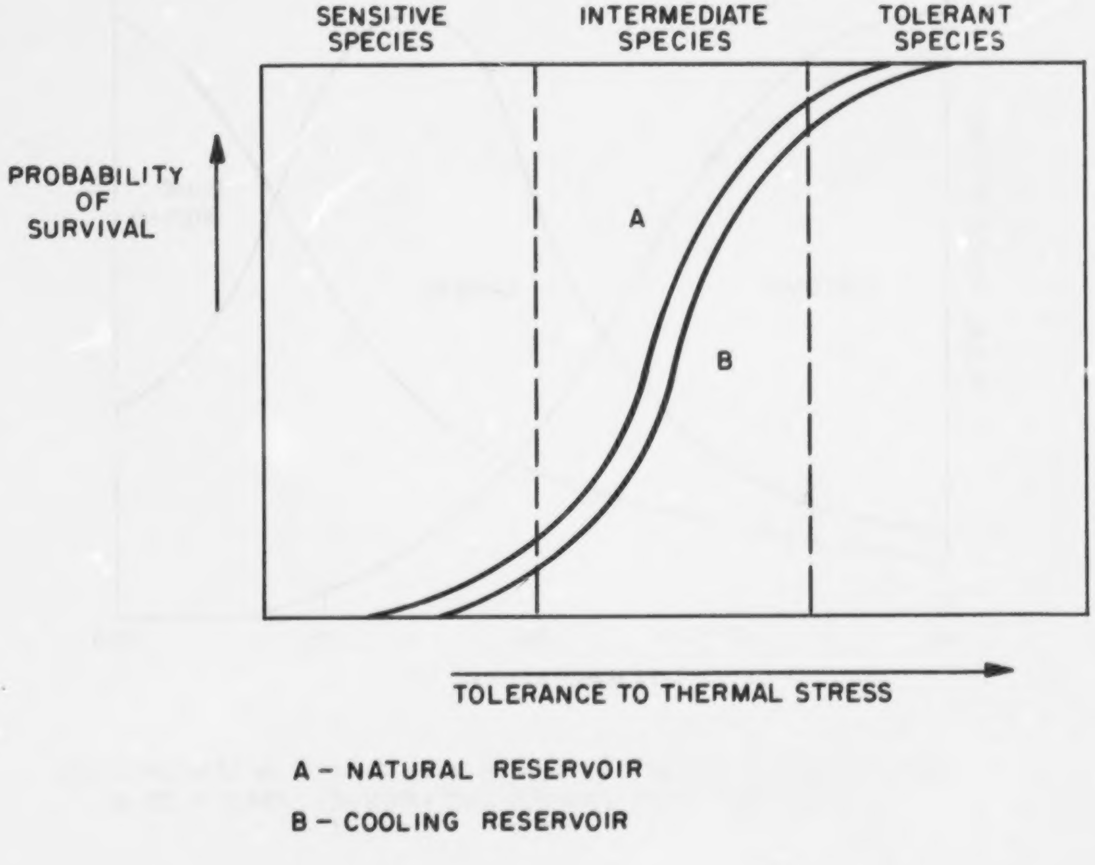
A – NATURAL RESERVOIR

B – COOLING RESERVOIR

119< EFFECT OF TEMPERATURE ON BIOLOGICAL PRODUCTIVITY

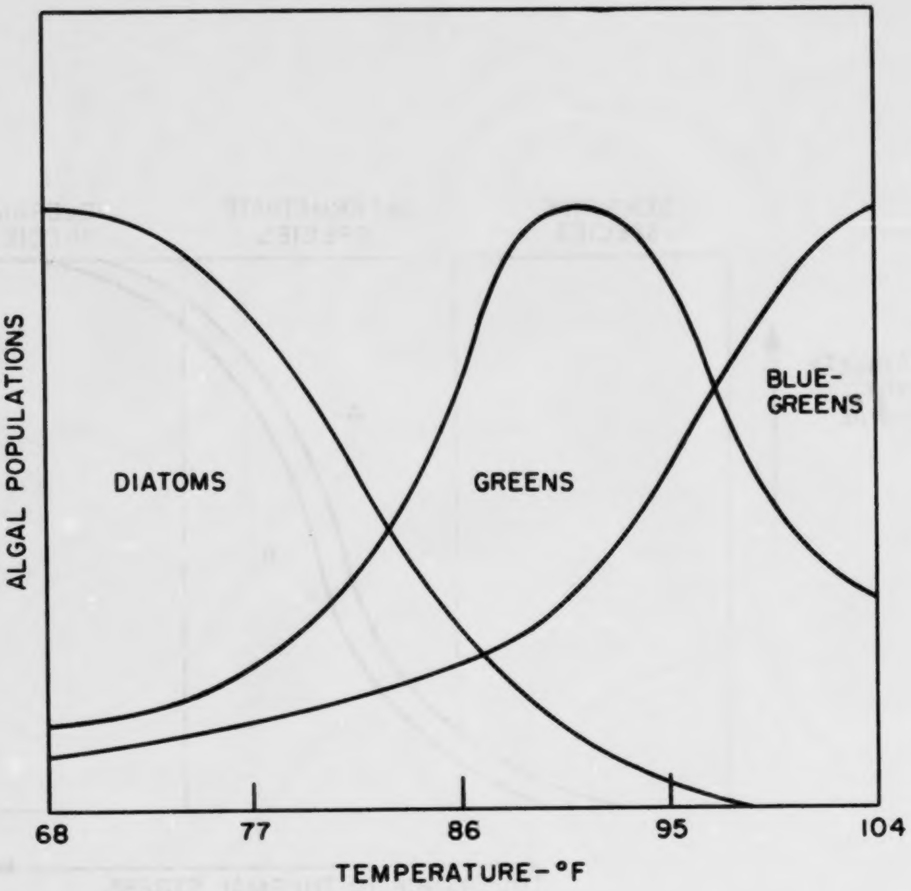
FIGURE 11

20



PROBABILITY OF SURVIVAL OF VARIOUS FISH SPECIES AT DIFFERENT TEMPERATURES

FIGURE 12



NOTE: ALGAL POPULATIONS SHIFTS WITH CHANGE IN TEMPERATURE
(ADAPTED FROM PARKER AND KRENKEL, 1969, P. III-8

| 121< | ALGAL POPULATION<br>SHIFTS | FIGURE 13 |
|---|---|---|

7-45-17

# BIOLOGICAL EFFECTS OF THERMAL EFFLUENT FROM THE CUTLER POWER PLANT IN BISCAYNE BAY, FLORIDA

R. C. Smith and H. J. Teas
Biology Department
University of Miami
Coral Gables, Florida 33124 U.S.A.

## ABSTRACT

The Cutler Plant is a fossil fuel power plant that discharges heated water into a small, shallow, partially enclosed portion of Biscayne Bay. An 11 month study was conducted on water and sediment temperatures, sediment character and benthic plants. Analysis of aerial photographs showed that there had been an increase in the area of bare sediment near the thermal discharge point from 8.5 ha the year (1956) when the full capacity of the power plant was reached to 35 ha in 1973. Ground truth checks indicated that the bare region at the effluent canal was an area of macrophyte loss, which corresponded to the highest temperatures. It was concluded that macrophyte elimination probably resulted both from direct thermal lethality and from the stress of increased turbidity present because of suspension of unvegetated sediments.

## INTRODUCTION

Industrialization in recent years has increased the number of power plants operating and planned in coastal sub-tropical and tropical areas. There has been considerable interest generated in the ecological impacts of the heated effluents from these facilities because of the higher temperatures to which organisms in the respective coastal waters are exposed. Two sub-tropical or tropical power plant sites that have been studied ecologically are the Turkey Point power plant on Biscayne Bay (Thorhaug, 1974 (1); Thorhaug et al., 1973 (2); Bader et al., 1970 (3); Roessler and Zieman, 1970 (4) including pre- and post-thermal discharge investigations (Thorhaug et al., 1975 (5) and a power plant at Guayanilla on the south coast of Puerto Rico where the effects of temperature on Thalassia has been investigated (Schroeder, 1975 (6).

Seagrasses are important components of the macrophytes at Guayanilla and Biscayne Bay. Thorhaug and others have recently reviewed the trophic role of seagrasses and summarized the effects of man on seagrasses (Thorhaug 1974 (1); Thayer et al. 1975 (7). Seagrass productivity can be the equal of many crops, and they may suffer from heated discharges, chemicals, turbidity, and other man-induced stresses. At both the Turkey Point and Guayanilla areas Thalassia was killed in the heated plume and was found to have reduced biomass in above ambient temperature zones near the plume. The present study is concerned with Cutler Power Plant, a fossil fuel power generating facility south of Miami on the western shore of Biscayne Bay, Florida. The general features of Biscayne Bay have been described recently by Thorhaug et al. (1973; (2). The Cutler plant is located about 16 km north of the Turkey Point Power Plant. It began operation in 1948 with two small units; others were added in 1950, 1955, and 1956 for a total capacity of 348 megawatts. The site location is shown in Fig. 1.

An ecological reconstruction of the effects of thermal discharge on algae and seagrasses of Cutler Bay is reported that utilizes recent observations coupled with interpretation of aerial photographs, the earliest of which was made 10 years before the Cutler plant was constructed.

## MATERIALS AND METHODS

Cooling water for the Cutler Power Plant is drawn from Biscayne Bay (see intake and discharge canals in Fig. 1). Information from the Florida Power and Light Company indicated that the cooling water passed through condensers at a peak rate of 869,000 liters/min with an average temperature increase of 7°. The heated water is discharged into a portion of Biscayne Bay, here called Cutler Bay, that is partially enclosed by Chicken Key and spoil banks from channel dredging.

Within Cutler Bay, ten sampling stations were established that represent an inner and an outer arc around the mouth of the discharge canal (see Fig. 2). Each station was sampled monthly from October, 1968 through August, 1969. Benthic plant material was collected by hand using diving equipment. Three samples each 1/30 $m^2$ were taken from the bottom of each station. Samples were sieved in the field and everything that was retained by a 3mm screen was taken to the laboratory for sorting. In the laboratory the species composition and relative abundance was noted and the volume of plant material was measured by displacement. Samples were also oven-dried.

Sediment depth was measured using a metal rod. Sediment samples were fractionated by wet sieving in the laboratory. Three fractions were separated: gravel-shell, >2mm; sand, 0.063 mm to 2 mm; and silt-clay, < 0.063 mm. Salinity of the water was measured in the field with a refractometer. Water and sediment temperatures were measured using a telethermometer. The distribution of the heated effluent in Cutler Bay was determined for several conditions of wind direction and tidal stage.

The average water depth in the study area was 60 cm, taken at mean low water. The mean tidal range in this area is approximately 58 cm (1.90 ft) (Schneider 1969 (8). The range of depths at the sampling stations was 28-86 cm. The combined effect of the wind, tide, and discharge were often associated with turbid water conditions in this shallow bay and, as a consequence, often the Bay bottom could not be seen from a boat.

The Dade County annual vertical aerial photographs, which are available from 1960 on, were used for analysis. A few earlier photographs were utilized. A photo-mosaic of Biscayne Bay was used for pattern comparisons. Ground truth observations were made by diving; biotic cover, sediment and water depth and other features were recorded and correlated with patterns on aerial photographs.

The areas of apparently bare sediment in Cutler Bay that lacked benthic macrophytes could be seen in the aerial photographs from years when the water was relatively clear. The regions of bare sediment were traced on translucent paper and their areas estimated by weighing the cut out papers.

## RESULTS

### Temperatures

The temperature of the intake channel was considered to be the normal (ambient) water temperature. The range of observed intake temperatures during the study was 17.8 - 29.4°; the temperatures of the discharge ranged from 21.6 - 41.1°. Bottom water or sediment temperatures were typically only slightly lower than surface temperatures. Thermal stratification within the bay was encountered occasionally on very calm days when differences as great as 3.3° were found between the warmer surface and bottom water.

An example of the distribution of the heated effluent, represented by isothermal lines, is shown in Fig. 2. Wind and tide were observed to cause lateral diversion, compression or extension of the heated plume, in the predicted directions.

## Salinity

Salinity variation at the Cutler Bay was similar to those reported for Biscayne Bay (Woodmansee 1958 (9); Smith et al. 1950 (10) i.e. a maximum of 37.9 ppt in March near the end of the dry season and a minimum of 18.8 ppt in July after heavy rains. No effect on salinity of the reported freshwater springs to the south (Kohout and Kolipinski 1962 (11) was observed.

## Sediments

The bottom of Cutler Bay has a variable covering of sediment which consists of calcareous sand and shell fragments in a matrix of organic mud. The mean sediment depth at the ten Cutler Bay sampling stations was 48 cm with a range of 11-86 cm for the individual stations. The substrate underlying the bottom sediments in Cutler Bay, and much of Biscayne Bay, is consolidated limestone that has many sediment-filled solution holes (Wanless 1974 (12). Where the sediment layer is thin, seagrass growth is limited to the sediment of the solution holes (Kelly 1969 (13). The mean values for sediment particle sizes in Cutler Bay were 8% for shell-gravel, 63% for sand and 29% for silt-clay.

## Macrophytes

The typical distribution of benthic macrophytes and blue-green algal mats of Cutler Bay is shown in Fig. 3. The Bay bottom in the area of the heated plume was bare except for algal mats.

Macrophyte standing crops as well as temperature data on the ten stations in August are shown in TABLE I. The seagrasses were the dominant plants. At one or another sampling, substantial amounts of the following macrophytes were found: Station 1, Halimeda sp. (Hal) and Diplanthera (Halodule) wrightii (Dip), Thalassia testudinum (Th); Station 2, debris; Station 3, Th, Hal, and Dip; Station 4, Digenia sp., Dip, Hal, Syringodium filiformis (Syr) and Th; Station 5, Dip and Hal; Station 6, Dip, Hal, Th and Laurencia sp.; Station 7, Th, Dip, Syr and Chondria sp. (Ch); Station 8, Th, Hal, and Ch; Station 9, Dip, Th, and Acetabularia crenulata; and Station 10, debris.

The lowest standing crops were found at Stations 1, 2, 5 and 10, which had the highest maximum water temperatures of the series (35.6 - 38.3$^{\circ}$), and the highest maximum sediment temperatures (35.0 -36.9$^{\circ}$). These stations also showed high average water and sediment temperatures.

Stations 2 and 10, which are nearest the heated outfall plume, had no benthic macrophytes. These stations showed water temperatures of 37$^{\circ}$ or higher at samplings in July or August.

Macrophyte standing crop data were tested for correlation with water temperature, water depth, salinity, sediment depth, sediment temperature and sediment composition (silt-clay, sand, and gravel-shell percentages). Significant linear and rank correlation coefficients at 5% or 1% level) (Snedecor and Cochran 1967 (14) were found only between macrophyte standing crop and sediment depth. Higher standing crop was correlated with deeper sediment and thin sediment was associated with reduced macrophyte crop.

## Aerial Photographic Analysis

A recent photomosaic of Biscayne Bay showed areas similar in pattern to those in various past and recent aerial photographs of Cutler Bay. A number of patterns at comparable water depth were checked for "ground truth" by diving. Types of bottom that can be recognized in Cutler Bay include:

(1) bare sediment (or sediment covered with blue-green algal mat, but having no macrophytes)

(2) seagrasses and soft-bottom algae (such as *Halimeda* and *Penicillus*) growing on moderately thick sediments

(3) sparse algae on thin sediments

(4) rolls of attached and unattached algae, as reported by Thorhaug (1974 (1)

(5) dense beds of *Thalassia* growing in sediment and often peat-filled pockets in generally thin sediment

One of the prominant features on aerial photographs of Cutler Bay was the area of bare sediment or sediment with blue-green algal mat extending from the thermal outfall canal. An example of such denuded area can be seen in the January 1962 aerial photograph (Fig. 4). The areas of such bare sediment were estimated for the years when water clarity permitted the limits to be traced; the results are shown in

TABLE II. The area of sediment bare of macrophytes in Cutler Bay increased during the years after the Cutler Power Plant was capable of full operation in 1956. By the 1960's the bare area had increased from 8.5 ha to the range of 22 - 30 ha.

In no year between 1965 and 1973 was the water sufficiently clear to trace the bare sediment area on the Dade County annual aerial photographs. The photograph for 1970, one of the years in which turbidity precluded estimation of the bare area, is shown in Fig. 4. In 1973 the denuded area was estimated to be 35 ha.

## DISCUSSION

Water temperature in the power plant effluent plume is clearly related to macrophyte survival. The surface water temperatures in Biscayne Bay ranged from about 18 - 29° during our study. Smith et al.(1950 (10) reported maximum temperatures of 30.5° at Chicken Key in August of 1945, so that ambient temperatures can probably vary 2 - 3° from year to year. Annual temperatures at Guayanilla, Puerto Rico ranged from 27 - 31° (Schroeder 1975 (6). We found relatively high standing crops of Thalassia at Station 8 where there were maximum (July and August) sediment and water temperatures of 35.2 and 35.6°. In August Station 1 had no leaves but live Thalassia rhizomes and Station 6 had a small amount of Thalassia. However, Stations 2, 5 and 10, where there were maximum sediment temperatures of 35.5 - 36.9° and maximum water temperatures of 35.6 - 38.3°, had almost no seagrasses or other macrophytes at any sampling date. Thus, our data suggest that the lethal summer water temperature for Thalassia at Cutler Bay was in the order of 35.5 - 36°. This is an approximate value: The location of the heated plume varied with wind and tide and temperature excursions between observations were not known. Schroeder (1975 (6) reported field studies of transplanted Thalassia plugs in Puerto Rico where he found that temperatures in the range of 35.0 - 36.4° were lethal in 7 weeks. Thorhaug (1974 (1) has obtained similar results for Thalassia lethality in studies at the Turkey Point plant on south Biscayne Bay, where she found that Thalassia disappeared where temperatures were 5° above ambient. The similarity of thermal death temperature estimates suggest that there is no substantial difference in high temperature tolerance of Thalassia in Biscayne Bay and Guayanilla, Puerto Rico. This could be anticipated from the similar water temperature maxima.

Sediment appears to be an important factor in macrophyte growth and distribution at Cutler Bay. Aerial photographs indicate that an increased cover of macrophytes has developed over much of Cutler Bay since 1938. We believe that this came about because of the deposition of sediment associated with deepening the boat channel at the northeastern side of Cutler Bay and dredging the power plant effluent canal. Macrophyte standing crop in Cutler Bay was positively correlated with sediment sediment depth. Indeed sediment deposition is known to favor seagrass growth. Odum (1963 (15) reported that partial cover of Thalassia and Diplanthera beds by silt from dredging reduced their productivity, but that in the following year productivity exceeded that of the predredging period.

Although Cutler Bay receives the power plant discharge, it has considerable protection from the wave action of Biscayne Bay proper and appears to serve as a sump for fine sediments, as evidenced by the high (av. 29%) silt-clay fraction for the ten Cutler Bay station compared to 0 - 5% (McNulty et al. 1962 (16) for samples from the open part of Biscayne Bay, to the east of Chicken Key, where there is much greater wave action. It should be noted that some of the fine sediment in Cutler Bay may be contributed by materials in the water that are precipitated or coagulated by passage through the power plant cooling condensers.

Bare areas on aerial photographs need to be interpreted cautiously. A bare area indicates sparse or no macrophyte cover, but it does not necessarily mean that macrophytes previously present are dead. For example, live Thalassia rhizomes, but not blades, were found in August at Station 1, where the temperature was high (maximum water temperature $36.1^{o}$, maximum sediment temperature $35^{o}$). During the previous winter and spring, leafed Thalassia and Diplanthera plants had been found at Station 1. Thus, Thalassia rhizomes may be viable for some time under temperatures that suppress leaf growth and may be able to resume growth under more favorable conditions.

Water turbidity must be an important factor in the growth of macrophytes in Cutler Bay. Out studies of aerial photographs suggest that changes in bottom of Cutler Bay after construction of the power plant came about by a series of events. The seagrasses, predominantly Thalassia, make up the major portion of the plant biomass at most stations in Cutler Bay. Benthic light levels are clearly involved in seagrass growth. It is well known that turbidity can limit seagrass crop (Strawn 1961 (17); Phillips 1962 (18); Moore 1963 (19); Odum 1963 (15);Thayer et al. 1975 (7). Before the power plant was built, Cutler Bay had a vegetation cover. Temperatures in the zone of the highest temperature part of the effluent plume are currently above those which are reported to be lethal to the macrophytes, so the absence of plants in this area is assumed to have resulted from thermal killing. It is known that water turbidity without thermal stress reduces yield in Thalassia (Thorhaug 1975 (20) and that Thalassia bind sediments (Wood et al. 1969 (21). We therefore hypothesize that the progressive enlargement of the bare area at the effluent canal, which occurred between 1956 and 1961, came about because temperature killed or reduced the viability of seagrasses or other macrophytes (Thorhaug 1974 (1), Thorhaug et al. 1975 (5), and thereby reduced sediment stability, which in turn caused water turbidity (Breuer 1962 (22); Thorhaug 1974 (1). Then, as the plants were stressed by turbidity-lowered light levels, they grew less productively or died causing more sediment to become exposed, which in turn resulted in more erosion and suspension of sediments and even more water turbidity. Thus, some of the benthic macrophytes may well have died from the combination of sublethal temperatures and turbidity, rather than temperature alone. If this is true, field observations of macrophytes may underestimate thermal death points.

Reduction in area of denuded bottom in the thermal plume region, such as occurred between 1961 and 1962, can be anticipated and may have simple bases. Studies at Card Sound, south of the Turkey Point Power Plant on Biscayne Bay (Thorhaug 1975 (20) have shown that plants became reestablished after an area ceased to be thermally stressed. Diplanthera and several of the macrophytic algae can become seeded and develop dense stands in less than a year. If thermal stress were reduced because of changes in water currents or reduced heat load, reduction of the bare sediment area might come about from any of several mechanisms: by development of plants from still viable roots or rhizomes, by reseeding of seagrasses or algae, or be vegetative proliferation of plants invading from cooler water and sediment areas.

## ACKNOWLEDGMENTS

The authors wish to thank the National Institute of Environmental Health Sciences and the Ford Foundation for support provided R. C. Smith, the Florida Power and Light Company for access to data, and Linda Sumarlidason for preparing the illustrations.

## REFERENCES

1 Thorhaug, A. 1974. Effects of thermal effluents on the marine biology of southeastern Florida. In: Thermal Ecology. J. W. Gibbons and R. R. Shavitz, (eds.). AEC Symposium Series (CONF-730505). pp. 518-531.

2 Thorhaug, A., D. Segar, and M. A. Roessler. 1973. Impact of a power plant on a subtropical estuarine environment. Mar. Pollution Bull. 4:166-169.

3 Bader, R. G., M. A. Roessler, and A. Thorhaug. 1970. Thermal Pollution of a Tropical Marine Estuary, FAO Techn, Conf. on Marine Pollution, Rome, E-4, pp. 1-6.

4 Roessler, M. A. and J. C. Zieman. 1970. The Effects of Thermal Addition on the Biota of Biscayne Bay, Florida. Proceedings of the Gulf and Caribbean Fisheries Institute, 22nd Annual Session, Miami, Fla. pp. 136-145.

5 Thorhaug, A., S. D. Bach, M. Josselyn, R. F. Hixon, and I. M. Brook. 1975. Thermal effluents from a power plant into Card Sound, Fla.: Effects before, during and after. Environmental Conservation In press.

6 Schroeder, P. B. 1975. Thermal stress in Thalassia testidinum. Ph.D. dissertation. University of Miami, Coral Gables, Fla. 158 pp.

7 Thayer, G. W., D. A. Wolfe and R. B. Williams. 1975. The impact of man on seagrass systems. Amer. Scientist 63:288-296.

8 Schneider, J. J. 1969. Tidal relations in the south Biscayne Bay area. Dade County, Fla. U.S. Geological Survey report. pp. 1-16.

9 Woodmansee, C. 1958. The seasonal distribution of the zooplankton off Chicken Key in Biscayne Bay, Fla. Ecology 39:247-262.

10 Smith, F. G. W., R. H. Williams, and C. C. Davis. 1950. An ecological survey of the substropical inshore waters adjacent to Miami. Ecology 31:119-146.

11 Kohout, F. A. and M. C. Kolipinski. 1967. Biological zonation related to groundwater discharge along the shore of Biscayne Bay, Miami, Fla. In: Estuaries, (ed. George H. Lauff). Amer. Assoc. Adv. Sci. Publ. No. 83:488-499.

12 Wanless, H. R. 1974. In: Environments of South Florida: Present and Past. Gleason, P. J., (ed.). Memoir 2. pp. 190-200.

13 Kelly, M. G. 1969. Aerial photography for the study of near-shore ocean biology. In: New Horizons in Color Aerial Photography. Amer. Soc. Photogrammetry. pp. 347-355.

14 Snedecor, G. W. and W. G. Cochran. 1967. Statistical methods. Sixth Edition. The Iowa St. U. Press. Ames, Iowa. p. 593.

15 Odum, H. T. 1963. Productivity measurements in Texas turtle grass and the effects of dredging on intracoastal channel. Publ. Inst. Mar. Sci. Univ. Texas 9:48-58.

16 McNulty, J. K., R. C. Work, and H. B. Moore. 1962. Level sea bottom communities in Biscayne Bay and neighboring areas. Bull. Mar. Sci. Gulf and Carib. 12:204-233.

17 Strawn, K. 1961. Factors influencing the zonation of monocotyledons at Cedar Key, Fla. J. Wildl. Mgmt. 25:178-189.

18 Phillips, R. C. 1962. Distribution of the seagrasses in Tampa Bay, Fla. Spec. Sci. Rep. Fla. State Bd. Conserv. 6:1-12.

19 Moore, D. R. 1963. Distribution of the seagrass Thalassia in the United States. Bull. Mar. Sci. Gulf and Carib. 13:329-342.

20 Thorhaug, A. 1975. Personal Communication.

21 Wood, E. J. F., W. E. Odum, and J. C. Zieman. 1969. Influence of seagrasses on the productivity of coastal lagoons. Lagunas Costeras. Un Simposio. UNAM-UNESCO, Nov. 1967. pp. 495-502.

22 Breuer, J. P. 1962. An ecological survey of the Lower Laguna Madre of Texas, 1953-1959. Publ. Inst. Mar. Sci., Univ. Texas 8:153-183.

TABLE I. WATER AND SEDIMENT TEMPARATURES AND STANDING CROP OF MACROPHYTES AT CUTLER BAY STATIONS

| Station | Dominant Macrophytes in August* | Standing Crop Av., g/m$^2$, d.wt. | Water Temp. Surface Range °C | Sediment Temp. Range °C |
|---|---|---|---|---|
| 1 | Th (rhizomes) | 57 | 20.8-36.1 | 21.6-35.0 |
| 2 | none | 5 | 22.0-38.3 | 22.5-36.9 |
| 3 | Th | 705 | 22.0-34.4 | 21.6-34.4 |
| 4 | Th | 154 | 21.7-34.4 | 21.6-32.5 |
| 5 | none | 7 | 19.4-35.6 | 19.7-35.5 |
| 6 | Dip | 227 | 21.1-35.3 | 19.1-34.7 |
| 7 | Th, Dip | 365 | 17.5-32.5 | 20.0-32.5 |
| 8 | Th | 705 | 19.4-35.6 | 19.1-35.2 |
| 9 | Dip, Th | 133 | 18.0-35.6 | 21.7-35.8 |
| 10 | none | 8 | 20.6-37.0 | 20.8-35.5 |
| Intake | --- | --- | 17.8-29.4 | --- |
| Effluent | --- | --- | 21.6-41.1 | --- |

* Th = *Thalassia testudinum*

Dip = *Diplanthera* (*Halodule*) *wrightii*

TABLE II AREAS OF BARE SEDIMENT ESTIMATED FROM AERIAL PHOTOGRAPHS

| Year | Area ha | Year | Area ha |
|---|---|---|---|
| 1956 | 8.5 | 1967 | * |
| 1960 | 29 | 1968 | * |
| 1961 | 30 | 1969 | * |
| 1962 | 24 | 1970 | * |
| 1963 | 22 | 1971 | * |
| 1964 | 28 | 1972 | * |
| 1965 | 27 | 1973 | 35 |
| 1966 | * | | |

* Insufficient water clarity for bare sediment area to be estimated.

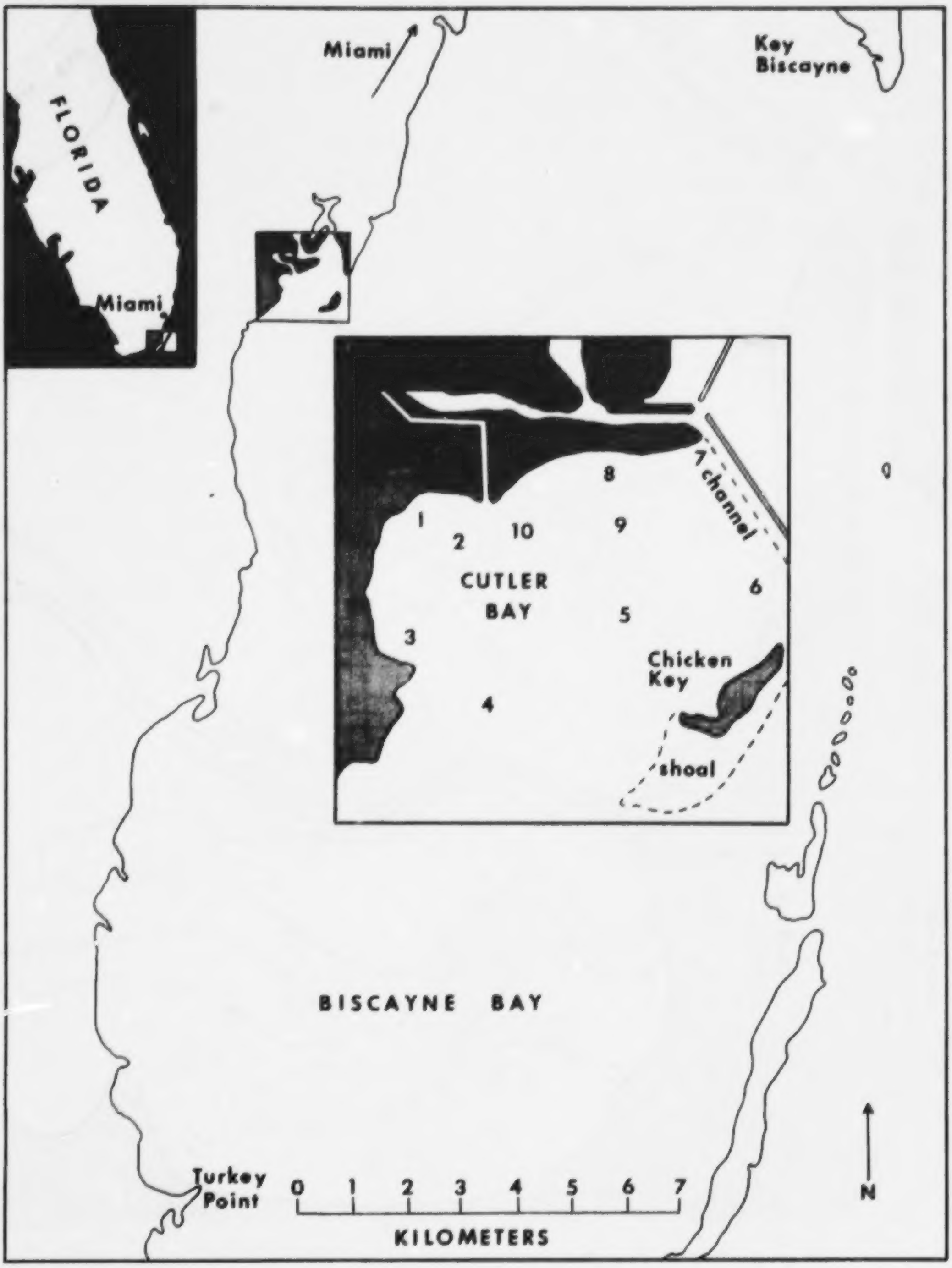

Miami
Key Biscayne
FLORIDA
Miami
1
2
10
8
9
7
channel
6
CUTLER BAY
5
3
Chicken Key
4
shoal
BISCAYNE BAY
Turkey Point
0 1 2 3 4 5 6 7
KILOMETERS
N

Fig. 1 Cutler Bay Location Map and Sampling Stations

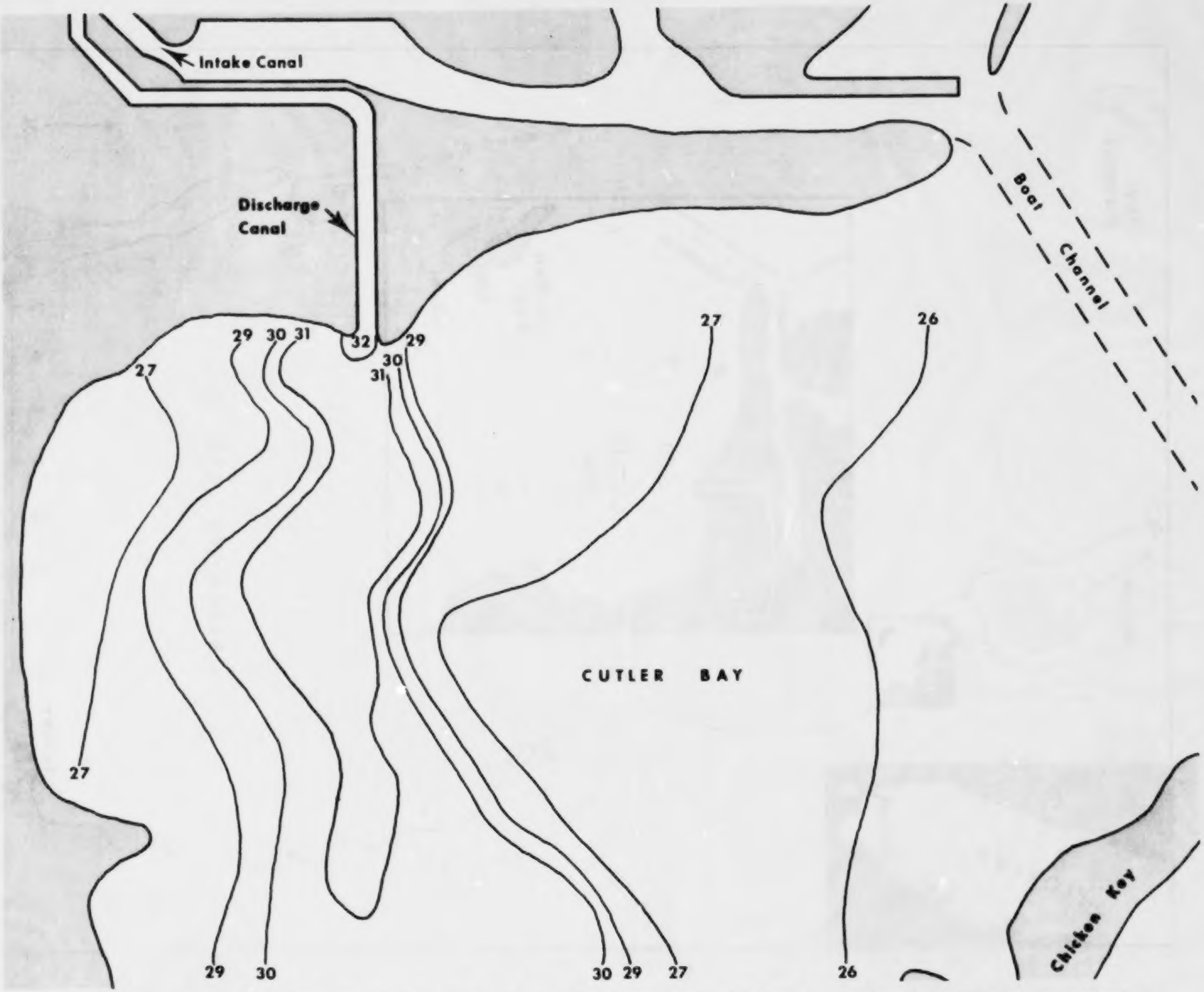

Intake Canal
Discharge Canal
Boat Channel
CUTLER BAY
Chicken Key
32
31
30
29
27
26
31
30
29
27
27
30
29
27
26
29
30
27

Fig. 2 Isotherms, $^{o}$C, May 19, 1970. Weather conditions: Winds from E to ESE, 20-23 km/hr; sea choppy; sky overcast. Plotted from 116 points.

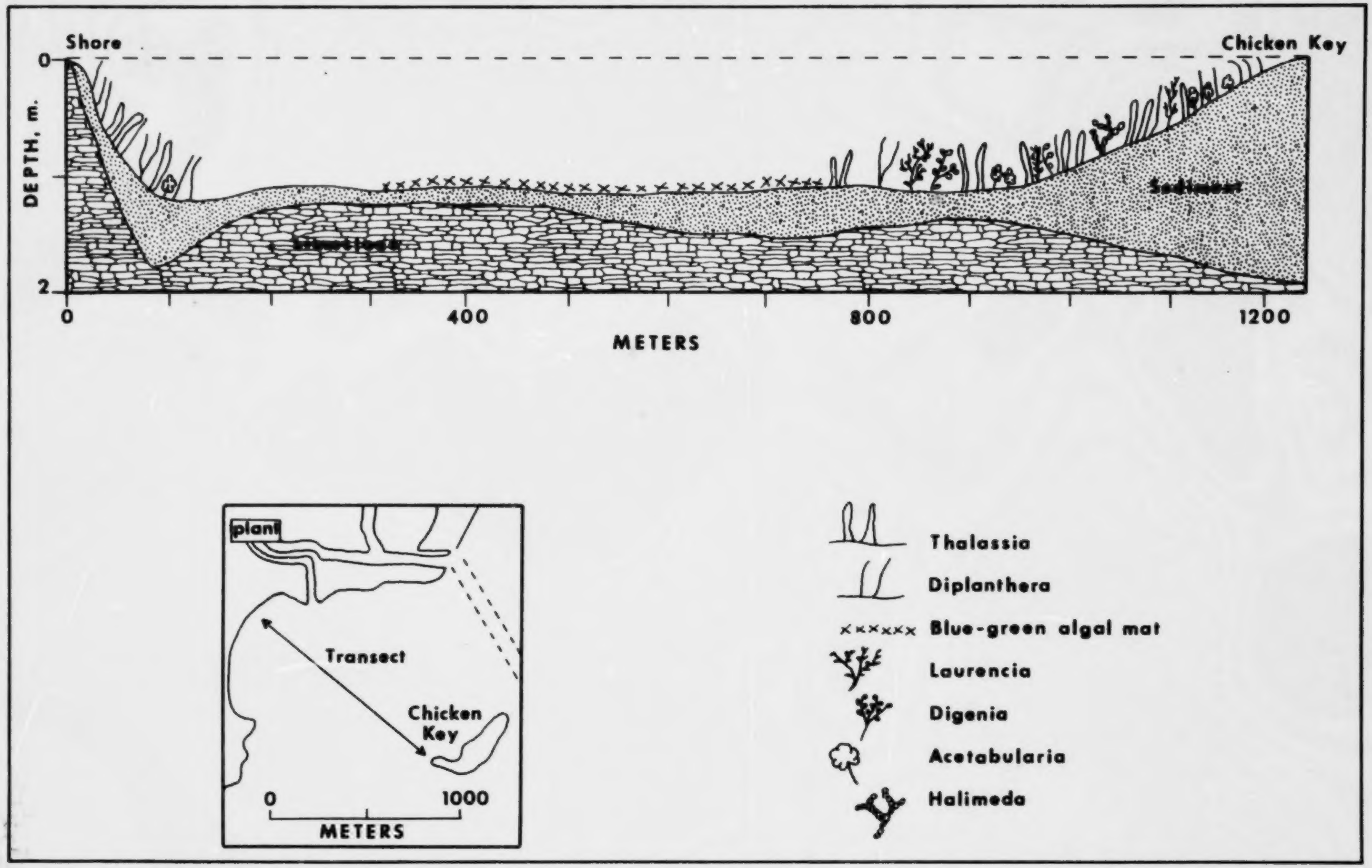

Shore
Chicken Key
DEPTH, m.
0
2
0
400
800
1200
METERS
Limestone
Sediment
plant
Transect
Chicken Key
0
1000
METERS
Thalassia
Diplanthera
×××××× Blue-green algal mat
Laurencia
Digenia
Acetabularia
Halimeda

Fig. 3 Vegetation transect across Cutler Bay

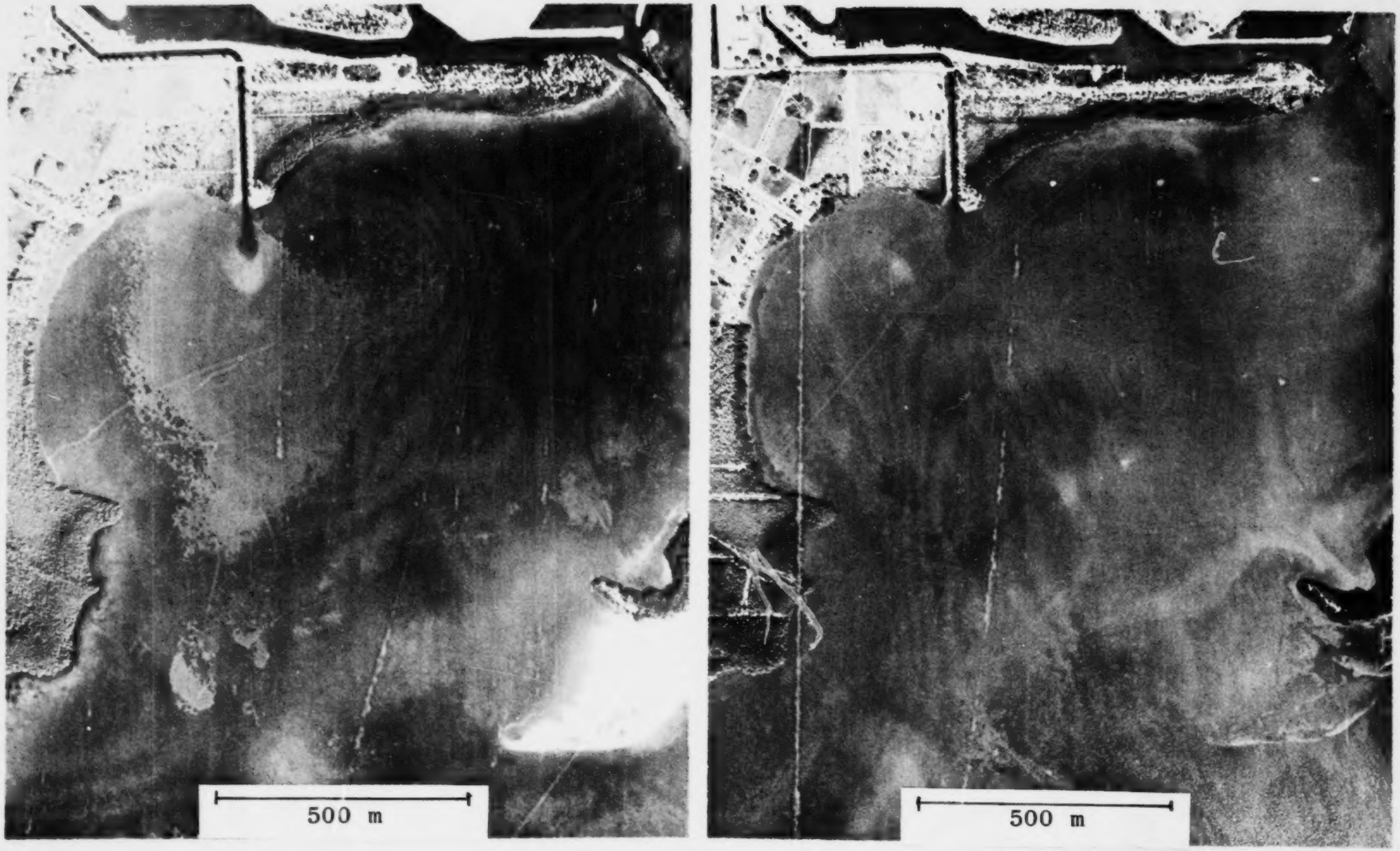


Fig. 4  Cutler Bay.  1962 Aerial Photograph (left), 1970 Photograph (right)

# SESSION II-C
## COOLING SYSTEMS I

8-45-28

# PROBLEMS OF DRY COOLING

F. K. Moore
Cornell University
Ithaca, New York U.S.A.

## ABSTRACT

Prospects for improvements of dry cooling systems are discussed, which might lead to greater acceptance by the utility industry. Following brief mention of promising system concepts, emphasis is given to purely technical questions, especially those of natural draft towers. A set of performance equations is presented, helpful for assessing performance penalties or benefits, and is applied to questions of aerodynamic losses in cooling towers. Flow improvements should lead to reduced tower size, less sensitivity to wind, and ultimatly to the design option of low, wide tower shapes. Problems of oblique flow in heat exchangers are discussed in terms of typical bundle configurations, and the importance of transverse uniformity at the tower exit is described. Possibilities for purely radiative heat rejection are discussed.

## INTRODUCTION

The rejection of heat from large power plants may be accomplished by the transfer of sensible heat from hot water to cooling air in a suitable heat exchanger, with no contact between air and water, and hence no evaporation. Such a "dry" cooling system would be preferable in comparison to the common evaporative "wet" tower, because

(a) Environmental impact is less; no local fog, rain, or extensive visible plume [1] would occur; the regional climate would also be less affected by dry cooling than by wet towers. Figure 1, adapted from [2], shows one set of calculations of the effects of a given area density of heat release on the climatic averages of surface temperature, cloudiness and precipitation, in a desert climate. These averages are disturbed much more by wet than dry cooling. In either case, the climatic impact would be significant only for several tens of GWe lined up in the path of wind, over a distance of a few hundred miles.

(b) Water consumption is virtually eliminated. The importance of this advantage depends on how seriously the consumptive water use of wet towers is viewed. For a typical 1000 MW plant, evaporative towers would consume the runoff from $34/r$ mi$^2$, where r is runoff rate in in./yr. If one is permitted to consume only 1% of a dry-climate runoff of 2 in./yr., then the "drainage area" of the power plant would be 1700 sq. mi.! In the northeastern U.S., if 10% of 34 in./yr. is allowed, only 10 sq. mi. is needed. One should bear in mind that in a typical 50-year drought period, stream flows may be down by a factor of 8 from normal, and competition for remaining water flow may be intense, even in the Northeastern U.S. Thus, for economically significant lengths of time, normally water-rich regions may become like deserts from a utility viewpoint.

Offsetting these advantages of dry cooling, one must consider a number of difficulties:

(a) The dry-tower air flow needs to be about 3 times that for a wet tower of the same capacity. The physical size of the tower, or the fan power in the case of mechanical draft, must be comparably large, with correspondingly high construction costs, or energy cost in fan-driven cases.

It should also be noted that the production of potential mechanical energy (buoyancy) in the plume is much greater for dry cooling, by a factor of about 12 in comparison with wet [3]. Thus, the question has been raised, whether dry cooling could generate local storm activity [4]. Indications are that such a thing is possible for heat releases comparable to volcanos and forest fires, which are known to generate storms. Probably, only plant concentrations of the order of 10-20 GWe could produce such results [4].

(b) A dry tower performs relative to ambient dry-bulb temperature, in contrast to a wet tower, which relates to wet-bulb temperature. Typically, design values might differ by 15°F. A loss of plant efficiency, or loss of capacity, follows [5]. The complex issue of how properly to model the cost of capacity loss has been reviewed in [6]. Typically costs of electric production are considered to be about 10% greater for dry cooling towers than for wet, when construction, energy, and capacity-loss costs are all considered [5,7].

(c) Dry cooling towers are apparently subject, more than wet towers are, to performance losses associated with variations of ambient conditions. The most obvious instance is the more extreme diurnal variation of dry-bulb temperature than of wet-bulb, in the summer when cooling conditions are more severe. Figure 2 shows the probabilities for a mid-continent location.

For less obvious reasons, wind and temperature inversions appear to affect natural-draft dry-cooling tower performance especially severely. Published data [8,9] for loss of cooling performance at Rugeley and Grootvlei stations may be arranged as in Figure 3 to show the effects. The consequent average diurnal production loss from these causes can be estimated [10], and an example appears in Figure 4, correlated with the peak demand profile for that location. Clearly, deleterious temperature and wind effects are severe, and unfortunately well-correlated with demand. Effects of inversions are less serious, apparently.

The result of balancing the advantages and disadvantages just described is, at the moment, and in the U.S., quite negative. In effect, the cost penalty is too great to swallow when the need, in terms of water consumption for the alternative wet system, is not overwhelming, and when the attractiveness, in terms of natural-draft tower size or mechanical-draft fan power and noise, is poor. However, in the rest of the world, especially the U.S.S.R., Hungary, W. Germany, Spain, and S. Africa, dry-cooling systems are being installed routinely; most popular seem to be the natural draft [8,9,11] and mechanical-draft air-cooled condenser (GEA) [12] types. The installation at Wyodak, Wyoming [13] is of the GEA type, and is the only reasonably large-scale U.S. dry-cooling project. It is noteworthy that existing dry-cooling installations typically serve rather small plants, up to the vicinity of 350 MWe, often in rather cool, dry regions.

In this paper, we will consider how prospects for dry cooling acceptance might be improved; especially how certain technical limitations might be removed from the path of progress (if, indeed, dry cooling can be considered progressive!). We will begin by briefly outlining directions of potential improvement, and singling out certain problems for rather detailed further discussion. As a final topic, we will consider the feasibility of radiative dry cooling.

## DIRECTIONS OF POTENTIAL IMPROVEMENT

In considering developments which might tend to favor dry cooling, we may distinguish between system ideas based on accepted engineering usage, and technical improvement aimed at widening the range of system options, or perhaps direct reduction of costs.

### System Considerations

(a) Plant Size: If siting pressures and demand slackening impel the industry toward smaller plant sizes, say 500 MWe or less, rather conventional dry cooling practice will be quite directly applicable, and perhaps more attractive. On the other hand, dispersed siting is easier to accommodate to environmental limits, including those on water consumption. Thus, several small plants may simply not need dry cooling as much as would a single large plant.

(b) Brayton cycle: If closed, regenerated gas-turbine cycles become more prevalent, dry cooling will be very attractive because the high gas temperatures entering the precooler will permit the initial temperature difference (ITD) of the cooling system to be very large, and the size of the system to be correspondingly small. This argument was put forward in connection with the General Atomic HGTR gas turbine cycle [14].

(c) Thermal Storage Ponds: The sensitivity of a dry cooling system to diurnal temperature changes can be eliminated by interposing a storage pond in the cooling circuit, of sufficient size to provide a daily-averaged temperature of condenser cooling water. To be effective, such a thermal capacitor would need to contain of the order of 6 hours-worth of condenser flow, namely about $3 \cdot 10^6$ $ft^3$ for a typical 1200 MWe nuclear plant. This possibility and some of its ramifications have been discussed in [15].

(c) Wet augmentation: It has recently been appreciated that cooling-load peaks, due to high mid-day temperatures in the summer, can be "shaved" by adding a minor degree of wet capability [16, 17], greatly reducing the required cooling capacity and cost of the dry system, with minimal water consumption, and probably acceptable costs of the additional wet capability. This option assumes at least some water is available. Wet/dry towers can be arranged in this way, but a separate wet tower is perhaps simpler, and occasional external flooding of suitably designed dry cooling coils is, in principle, simpler yet [18].

## Technical Considerations

(a) Tower and heat-exchanger dimensions: If tower size (or fan power) could be reduced, costs would go down and aesthetic acceptability would be improved. Likewise, heat-exchanger size contributes heavily to cost, though costs related to tower size are typically greater [19] by a factor of about 2. Heat exchanger size may best be expressed in terms of total air-side heat exchange surface area. Quite apart from tower "size", one may ask how the "size is manifested: Perhaps a low, broad tower would work as well as a tall, narrow one, and be much more acceptable visually.

(b) Heat-exchanger innovations: Fin-tube heat exchangers are customary, but other types, such as large discs [20] and pebble-beds [21] have been considered. These seem not very promising. As in so many other heat-exchanger applications, fouling is a painful limitation. Studies have suggested that if ammonia were used in the cooling circuit instead of water, size and cost savings could result, provided corrosion problems are manageable [33]. This possibility, though potentially very important, will not be discussed here.

(c) Aerodynamic Problems: Cooling towers are designed on the basis of one-dimensional duct flow, both as regards the bulk flow through the tower and its emergence into the ambient air, and as regards air passage through heat exchanger bundles. Actually, the typical cooling tower of natural-draft type is perhaps too low and broad to qualify as a one-dimensional duct. Mechanical draft towers typically have an equivalent draft height two or three times that of natural-draft towers, so perhaps duct-flow assumptions are more valid in those cases. Heat-exchanger bundles are arranged in various configurations, according to art and experience, but usually with faces quite oblique to the oncoming flow.

Solving aerodynamic problems associated with the failure of tower flow to conform to duct-flow assumptions would be important in at least three ways: (1) The basic design may be made more efficient. For example, it has been suggested [22] that 37 percent of exit total head be assumed as an additional loss due to various causes not covered by duct-flow analysis. If one could eliminate this need for over-design, construction costs could be reduced. (2) Similarly, costs could be reduced if over-design were not needed to compensate for the wind effects displayed in Figures 3 and 4. Again, such aerodynamic advances would be especially important for natural draft towers, because through velocities are typically 2 or 3 times lower than those in mechanical draft. (3) With improved aerodynamic design, lower, broader towers would be feasible, and aesthetic and cost improvements would result. Occasionally, extremely low towers are postulated without discussing their aerodynamic limitations [23].

(d) A final possible direction of technical development in dry cooling is to include a radiative feature; in effect using a surface which reflects solar radiation but is black for long-wave radiation, to exchange heat with the water vapor in the surrounding atmosphere [3].

In the remainder of this paper, we will explore the directions of technical improvement just described, beginning with the requirements for draft and heat exchange, continuing to a discussion of flow problems; and concluding with the matter of radiative heat rejection. Natural draft will be emphasized, because it would seem that such towers have more room for improvement.

## REQUIREMENTS FOR DRAFT AND HEAT EXCHANGE

In outline, we will follow the discussion of draft contained in [3]. For the simple tower sketched in Figure 5, if flow is one-dimensional, with ambient pressure matched at the exit, and air temperature changes are small, the following simple natural draft equation applies:

$$\left(\hat{Y} - \frac{C_D}{\alpha^3 \hat{A}_H^2}\right) \hat{A}_E^2 = \frac{1}{\alpha^3} \qquad (1)$$

where height $Y$ and duct areas $A_H$ and $A_E$ at the heat exchangers and at the exit are made dimensionless by use of a length $\ell \equiv [Q(2g)^{-1/2}(\rho C_p T)^{-1}]^{2/5}$, which is a measure of the heat rejection requirement $Q$. Thus, $\hat{Y} \equiv Y/\ell$, for example, and tower dimensions will scale as $Q^{2/5}$. $C_D$ is the overall pressure-drop coefficient across the heat exchangers, and $\alpha$ is the air temperature rise in proportion to absolute ambient temperature. For mechanical draft, $\hat{Y}$ may be replaced by a quantity proportional to the ratio of fan power to $Q$.

Eq. (1) balances buoyancy (first term) against head losses in the heat exchanger (second term) and the head loss in the exit jet. Clearly, if there were no heat-exchanger pressure drop, a minimum "size" results governed by the exit head drop, namely $(\hat{Y}\hat{A}_E^2)_{min} = 1/\alpha^3$. Evidently, duct diameter is much more important than tower height, and one would be encouraged to make the duct short (small $Y$) and wide in order to save construction costs and reduce visual impact. However, the equation assumes one-dimensional flow, which would be invalid for short ducts, especially in the presence of wind. If we fix a tower shape factor $s \equiv YA_E^{-1/2}$, then the minimum size is given by

$$\hat{A}_{E\ min} = s^{-4/5}\ \alpha^{-6/5} \qquad (2)$$

How may the minimum tower size be achieved or approached? If $C_D$ is expressed in terms of heat-exchanger quantities, one finds [3]

$$C_D = \alpha^3(A_H/A_C)^2(f/St)(E/F)\Psi I^{-3} \qquad (3)$$

where $A_C$ is the free-flow area of the heat exchanger, which in principle can be much larger than the duct area $A_H$, if the heat exchanger is highly folded; f/St is the ratio of friction factor to Stanton number, which practically must be at least about 2; E/F is a quantity which is near 1 if fin efficiency and counterflow equivalence is near 1; $\Psi$ is a certain function of $\alpha$ and of cooling-water "approach" P; and I is the ratio of ITD (hot water vs. ambient air) to absolute air temperature. A large value of I will tend to minimize tower size, as will a large value of $A_E$.

Of course, increasing I will increase condenser temperature and lower plant efficiency, and increasing $A_C$ will perhaps increase heat exchanger size, and certainly will make it difficult to "package" the heat exchanger in the tower. Thus, large values of I or $A_C$ are not necessarily good, even though a small tower size seems to result. In [3] it is pointed out that the air-side heat exchange area is given by an expression in which the chief dependence on heat-exchanger geometry is in terms of the "free-flow volume" $A_CL_a$:

$$A_a \propto (A_CL_a)^{1/2} \qquad (3)$$

where $L_a$ is the depth of the heat exchanger.

If $A_a$ is taken as a measure of heat exchanger size and cost, then one would like $A_CL_a$ to be small. But if $A_C$ is also to be large to make tower size small, then $L_a$ must be extremely small. It turns out [3] that such a shallow heat exchanger must be very fine as well; that is, have a very small air-side hydraulic diameter. In other words, we argue that use of a very fine heat exchanger could simultaneously reduce tower size and heat exchanger size.

Unfortunately, fouling considerations forbid taking real advantage of this principle. However, perhaps one day a self-cleansing heat-exchanger will appear, and the foregoing minimization principles may find application. It may be worth keeping in mind that a cooling tower differs from the usual compact heat exchanger application in that frontal area (hence $A_C$) is not so limited by the machine of which it is a part; in other words, the tower itself will dwarf the heat exchanger in any case. Thus, shallow heat exchangers are especially desirable for cooling towers.

To see the relation between tower size ($A_E$) and heat exchanger size ($A_a$) for certain heat exchanger surfaces, air and water side heat-exchanger analyses, subject to the draft equation already described, were carried out [3], and certain of the results appear in Figure 6. The spine-fin surface was the finest surface considered, having a hydraulic diameter of 0.0094 ft. and a depth per row of 0.077 ft. The Forgó heat exchanger [8] has a hydraulic diameter of about 0.012 ft. and a depth of 0.5 ft. (for 6 tube rows). A many-row bank of bare 3/8 in. ID tubes was also considered, with hydraulic diameter of 0.069 ft. and a depth per row of about 0.035 ft. Additional conditions of the calculations were those listed in Table 1. Essentially, the calculations postulated a tower of given shape, handling about 1/12 the heat to be rejected from a 1000 MWe nuclear plant.

At the various points on Figure 6, the ratio of $A_E$ to its minimum value (eq. (2)) is given, with the ratio of frontal area ($A_f$) to $A_E$, and the cubic feet of material needed to make the heat-exchange surface.

For a given heat-exchanger surface type, one may choose a large heat exchanger and small tower, or vice versa. Presumably, economics will dictate the choice. We notice that for a given tower size, the Forgó device has the least packaging problem ($A_f/A_E$ is small), and the 10-row plain tube surface is the most difficult to fit. Heat exchanger material is apparently least for the spine-fin surface.

If, following Rossie and Cecil [22], we assign an additional head loss of 37% at the exit due to aerodynamic effects in the tower, the tower height and diameter will both need to be increased by about $(1.37)^{1/5}$ or 1.07. The extra 7% in dimensions indicates the potential savings achievable by aerodynamic improvement of the tower and heat exchanger. Two such points, improved and unimproved, are shown for Rugely on Figure 6.

## SIMILARITY RULES AND OPTIMIZATION

In [3], [24] and [25] we have developed quite general formulas that represent the calculations displayed in Figure 6. First, we specify some heat exchanger geometry; that is, a given surface and given bundle configuration, but, of course, we allow number of bundles, and hence $A_a$, to vary. Then, it turns out that both $A_a$ and $A_E$ can be represented very well as functions of the ratio

$$A_E/A_{E\ min} \equiv \xi \qquad (4)$$

(which we will denote $\xi$ for convenience) multiplied by functions of the various parameters of the problem, such as Q and I. In other words, a "separation of variables" applies, for both $A_E$ and $A_a$. This result emerges from "exact" calculations, which in turn suggest certain analytical approximations [25].

It can be shown that if the heat-exchanger performance can be represented by powers of Reynolds number,

$$f = f_o R^{-x}, \quad St\,\eta = (St\,\eta)_o R^{-y} \tag{5}$$

where subscript o represents reference values of friction factor and the product of Stanton number and fin efficiency, and if the exponent x is fairly small, say 1/4 (it is .275 for the 2-pass spine fin surface), then the following proportionalities apply:

$$A_E^{\frac{5}{6}(1+\frac{1}{5}k)} \propto \left[\xi^{\frac{2}{3}(1-k)} (\xi^2-1)^{\frac{k}{2}}\right] \left[Q^{\frac{2}{3}(1+\frac{1}{2}k)}\, I^{-1}\, s^{-\frac{1}{3}(1-k)} \left(\frac{P}{I}\right)^{-\frac{m}{3-n}} \right.$$

$$\left. \times\ f_o^{-\frac{k}{2}} (St\,\eta)_o^{-\frac{1}{3-n}}\, p_w^{-\frac{2}{35(3-n)}}\, \beta^{\frac{1}{3}(1+\frac{1}{2}k)}\right] \tag{6}$$

$$(A_a/A_E)^{2-x} \propto \left[\xi^{\frac{4}{5}x} (\xi^2-1)^{-1}\right] f_o\, \beta^{-1} \tag{7}$$

$$L_w^{\frac{14}{9}} \propto A_a\, Q^{-1}\, (I-P)^{\frac{14}{9}}\, p_w^{\frac{5}{9}} \tag{8}$$

where n and m are exponents describing counterflow equivalence [25] which are generally about 1 and 3/4 respectively. k is a number depending on x, y, and $\eta$, and is generally around 0.2. $p_w$ is the ratio of water-pumping power to Q. The distance between water headers in the bundles is $L_w$. The factor $\beta$ is head loss in the tower, as a multiple of exit total head. It is remarkable that so little information is needed about the tower and heat exchanger to produce such detailed descriptive equations.

These equations can be regarded as means of evaluating changes away from some initial solution (perhaps a point on Figure 6), either as the result of a design change, or as a performance change due to fluctuations of ambient conditions. First, we consider the design implications of eqs. (6-8). The fact that, for a given heat exchanger type, $A_a$ and $A_E$ are in a ratio which depends only on $\xi$ (eq. (7)) implies that the best balance between them (in effect, the best $\xi$, which defines a choice of best point along one of the curves in Figure 6) can be made once and for all, whatever the values of such other parameters as I or s. This point is discussed in [26], and more fully in [25].

For the choice of $\xi$ to be explicit requires that tower costs can be assigned either to the tower size $A_a$ or the heat exchanger size $A_E$, in the form of coefficients $C_a$ or $C_E$ in cost per unit area. For the spine-fin heat exchanger cited in Figure 6, the optimum $\xi$ varies from about 1.2 when $C_a/C_E = 0.2$ to about 1.5 when $C_a/C_E = 0.8$. After the best $\xi$ is found, the best values of the other parameters in eq. (6) can be found in terms of other costs; for example, best I would depend on cost assigned to loss of plant efficiency when I is increased. Figure 7, from [24], shows the sensitivity of overall costs calculated in this way, to various construction cost coefficients. Clearly, $C_E$ (tower size) is most important - about twice as important as $C_a$ (heat exchanger size) or cost of pipe diameter (for headers). Cost coefficients for the condenser and pump sizes are even less important. Figure 7 suggests, in other words, that the most significant dry-cooling construction-cost reductions could be achieved by reducing the cost of the tower itself.

## PERFORMANCE EFFECTS AND FLOW PROBLEMS

For purposes of further discussion, it is convenient to convert eqs. (6-8) into equations relating small changes (signified by $\Delta$). In this way, we can eliminate changes of $\xi$, leaving only two simultaneous difference equations:

$$\left[\frac{2}{3}\left(1+\frac{1}{2}k\right) + \frac{2}{35(3-n)}\right]\frac{\Delta Q}{Q} - \frac{\Delta I}{I} - \frac{m}{3-n}\,\frac{\Delta(P/I)}{P/I}$$

$$-\frac{2}{3}\left[1+\frac{1}{2}k - g\left(1-\frac{1}{2}x\right)\right]\frac{\Delta A_E}{A_E} - \frac{2}{3}g\left(1-\frac{1}{2}x\right)\frac{\Delta A_a}{A_a} - \frac{1}{3}(1-k)\frac{\Delta Y}{Y}$$

$$\frac{1}{3}\left(1+\frac{1}{2}k-g\right)\frac{\Delta\beta}{\beta} + \frac{1}{3}\left(g-\frac{3}{2}k\right)\frac{\Delta f_o}{f_o} - \frac{1}{3-n}\,\frac{\Delta(St\ \eta)_o}{(St\ \eta)_o} = 0 \qquad (9)$$

where pumping power is assumed constant. If $L_w$ is also held constant,

$$-\frac{9}{14}\frac{\Delta A_a}{A_a} + \frac{\Delta Q}{Q} - \frac{\Delta I}{I} + \frac{P}{I-P}\,\frac{\Delta(P/I)}{P/I} = 0 \qquad (10)$$

where g is a function of $\xi$:

$$g \equiv \frac{\xi^2-1}{\xi^2}\;\frac{1+\frac{k}{2}\,(\xi^2+2)/(\xi^2-1)}{1-\frac{2}{5}\,x\,(\xi^2-1)/\xi^2} \qquad (11)$$

By way of example, we note that if ambient temperature changes slightly, so that I changes, the heat rejected for a given tower is obtainable directly by eliminating approach P between eqs. (9) and (10). Because the tower is given, Q and I are the only other variables. The result for Rugeley parameters ($P=(0.47)I$, $m=0.6$, $n=1.0$, and $k \approx 0.2$), is

$$0.81 \frac{\Delta Q}{Q} = \frac{\Delta I}{I} \tag{12}$$

which agrees with the observed power law cited for Rugeley in [23], except that the coefficient given there is 0.79.

Next, we consider the effect of the exit-loss factor $\beta$, which is 1 for an ideal tower, but is greater for a real tower with various duct and heat-exchanger losses; we have already mentioned the value 1.37 suggested in [23]. With all duty and heat-exchanger parameters held fixed, with $n=1$, $m=3/4$, $k=0.2$, $x=0.275$, $\xi=1.41$, and $P/I=0.5$, we ask how design requirements change as a result of $\beta$ being different from 1. Eliminating $\Delta(P/I)$ between eqs. (8) and (9), we find

$$\frac{\Delta A_a}{A_a} + 0.46 \frac{\Delta A_E}{A_E} + 0.40 \frac{\Delta Y}{Y} = 0.18 \frac{\Delta \beta}{\beta} \tag{13}$$

Thus, if $\beta$ were decreased from 1.37 to 1 (eliminating all duct losses), $A_a$, $A_E$, or $Y$ could each separately be decreased by 7, 14, or 17 percent, respectively. If "shape" $Y/\sqrt{A_E}$ and $A_a$ were held fixed, then dimensions could be decreased by 5 percent. These numbers, while only approximate, do suggest the level of improvement achievable by reducing duct losses in the tower.

In the case of an existing tower, perhaps some ambient change, such as wind, would affect the rate of heat release. In that case, we allow only Q, P, and $\beta$ to change, and find, for the same parameters as before, that

$$\frac{\Delta Q}{Q} = -0.11 \frac{\Delta \beta}{\beta} \tag{14}$$

so, if $\Delta\beta/\beta = -0.37$, heat rejection would improve by about 4 percent.

In [25], eqs. (9) and (10) are used to describe plant performance changes resulting from imposed changes that can be described by categories collected in the second and third lines of eq. (9). For example, perhaps wind effects can be represented by an increase of friction factor $f_o$. The following formula was used to represent the effect of changes of cycle rejection temperature $(T_a+I)$ ($T_a$ is ambient temperature) on the rate of heat rejection:

$$\frac{\Delta Q}{Q} = 2\eta_o \frac{\Delta T_a + \Delta I}{T_a + I} \tag{15}$$

Here, $\eta_0$ is the undisturbed cycle efficiency, and the factor 2 is an empirical choice which reflects typical turbine performance. One then finds that if observations of wind effect and inversion effect can be put in the form which follows, D and G being unknown constants,

$$\frac{\Delta I}{T_a} = Dw^2 + G(\Delta T_i + 0.010Y) \qquad (16)$$

where w is wind speed and $\Delta T_i$ is temperature inversion ($\Delta T_i$ = -1.0 °C would be the adiabatic lapse for a tower height of 100 m.), the corresponding output penalty would be nearly

$$\frac{\Delta Pe}{Pe} = -2(1-\eta_0)\left[\frac{\Delta T_a}{T_a} + Dw^2 + G(\Delta T_i + 0.010Y)\right] \qquad (17)$$

A somewhat more accurate application of eqs. (9) and (10) is provided in [25].

Observations at Grootvlei and Rugeley [8,9] are fairly well represented by eq. (16), as indicated on Figure 3. For Grootvlei, $D \approx 1.1 \cdot 10^{-4}\ (m/s)^{-1}$, and $G \approx 2/3\ T_a^{-1}$. With those choices, eq. (17) provides the estimate shown on Figure 4. We will not pursue this line of performance analysis further in this review; in summary, one may reasonably hope to interpret observations of tower performance fluctuations through use of eqs. (9) and (10), which can then serve as a kind of meeting ground between in-plant observations and explanatory physical theory or experiment.

We next consider some of the total-head loss mechanisms that appear to be significant for dry cooling towers, in terms of both basic design and response to ambient fluctuations.

### Effects of Atmospheric Inversions.

First we offer a possible explanation for the rather striking effects of atmospheric inversion reported at Grootvlei [9]. Changes of I were found ranging from about 1/4 to about 5/6 of the inversion itself (excess of temperature at tower at exit over ground ambient). Apparently, severe inversions are encountered there; at U.S. locations, inversions large enough to substantially change I are fairly rare, as reflected in the rather low impact predicted in Figure 4.

One first thinks of the fact that inversion implies that the lighter air will provide less driving pressure difference for tower flow. Incorporation of this effect in eqs. (9) and (10) proves capable of representing only the lower bound of the observations, $\Delta I/(\Delta T_i + 1.0) \approx 1/5$. The most likely explanation for the higher data seems to be that the average virtual source of the entrance air is at a level above the entrance; thus, the entering air is actually hotter than ground-level ambient, and therefore the actual I is smaller than the apparent I based on ground level ambient. Relative to operation with the latter value, the tower would suffer a performance loss. This model suffices to explain the data, provided the "virtual source" is of the order of half the tower height (100 m.). Density stratification of the incoming flow would tend to oppose this effect, and it would seem reasonable to keep the fetch of entering air free of ground obstructions, in order to preserve a stratified (cool) sink, if possible.

## Effects of Flow Obliqueness.

As we have seen, packaging of heat exchanger bundles in a tower-base region can provide a geometrical puzzle. Typical solutions (sketched in Figure 8) involve basically internal, horizontal arrays as at Grootvlei [9] or external vertical columns as at Rugeley [8]. In either case bundles are set in "delta" positions, with included angles of 60° being customary. It is not clear what loss penalties should be ascribed to these arrangements, in view of the oblique approach of air to the bundles. Even when flow direction is well defined by a surrounding duct, basic technical data about oblique losses is not plentiful [27, 28]; in a tower, the flow passage is of very large scale and directions of flow are less controlled, or even known, especially when the wind blows. It should be noted that typical tower entrance velocities are only about 2.4 m/s, and the "free-flow" velocity through the oblique bundle is about the same (less because of obliqueness, more because of the solidity of the heat exchanger), while average wind speeds in most locations are about 4 m/s. Thus, it should be expected that flow obliqueness would vary markedly with wind.

For heat exchangers with large pressure drop, the flow is quickly forced to assume a direction normal to the face as it proceeds through the exchanger body. Therefore, the important question about oblique flow approach, whether due to wind or not, is whether the transverse component of velocity is irreversibly lost in the heat-exchanger entrance; if it is, then to that degree, driving total pressure is lost. If it is not, that is, if the flow turns into the heat-exchanger face in such a way that dynamic pressure associated with transverse velocity is recovered, then the heat exchanger suffers no oblique-flow penalty whatever. In fact, if transverse velocity due to wind is so converted, wind effect should give a performance gain, at least for the heat exchanger.

Heat exchanger pressure drops in the Grootvlei and Rugeley towers, though both high, are quite different; the overall pressure drop is about 35 dynamic heads based on 2.3 m/s at Grootvlei, and only about 13 at Rugeley. These high pressure drops of course mean that through flow is established at least fairly well, whatever incidental disturbances may occur that are of the order of the dynamic head of the oncoming flow. Gross separations of flow are unlikely, for example. Nevertheless, a loss of one dynamic head constitutes a potential penalty of 3 percent at Grootvlei and 8 percent at Rugeley, which can be very serious in terms of performance.

A simple theoretical formula that conforms quite well to available data [25] is

$$1 - \frac{(P_o - P_1)\ \text{actual}}{(P_o - P_1)\ \text{ideal}} = \left(\frac{1-\cos\theta}{\sin\theta}\right)^2 \qquad (18)$$

which refers to the excess of pressure just inside the face of the heat exchanger (Po) over the pressure in the oncoming flow ($P_1$) . The obliqueness of approach is denoted by $\theta$; for normal approach, $\theta=0$, and recovery is complete. For purely transverse approach, $\theta=90°$, and loss is complete. When $\theta=60°$, the loss is only 33 percent, by eq. (18). Thus, we are chiefly concerned with the accidental occurence of angles approaching 90°, and we should keep in mind that any loss of pressure represented by eq. (18) will usually be a fairly small fraction of overall pressure drop.

Figure 9 illustrates the sort of flow pattern to be expected when flow obliquely approaches a "delta" arrangement. Potential streamlines were calculated on the basis of an infinite pressure drop, which implies a constant normal velocity component at the exchanger face. Notice that the flow is highly distorted near the leading corner; in fact, transverse potential-flow velocity becomes infinite there. Obliqueness ($\theta$) is noted on the figure, and the pressure loss ratio from eq. (18) is also noted. If the flow were not oblique to the delta, $\theta=45°$ for both faces and the loss ratio would be only 0.17. Clearly, the face toward the flow has less loss than that, and the face away from the flow has more.

Armed with these general ideas, we can draw inferences about the performance penalties of obliqueness in certain situations. In wind, an external cylindrical array of bundles as at Rugeley [8] or Ibbenbüren [11] even without the delta treatment, experience the high transverse velocities associated with flow around a cylinder, ideally twice the wind velocity at the shoulder. If the wind should be 5 m/s, the transverse component would be about five times the normal component of 2.3 m/s. Thus, $\theta \simeq 77°$, and the loss ratio by eq. (18) would be about 63 percent. Since the dynamic head of the transverse component would be about 19 times the dynamic head of the normal flow, about 12 dynamic heads would be lost, and 13 are needed just to push the flow through the heat exchanger! As a result, much of the heat exchanger array will be stalled and ineffective, as is reported in [8]. The delta feature presumable makes matters worse.

Presumably, the internal bundle configuration of the Grootvlei type is sheltered from wind by the tower skirt, and in any case is not subject to the high shoulder velocities of an external array. However, it should be noted that when the wind becomes very high, the windward bundles at Rugeley presumably are increasingly effective, while shoulder and leeward bundles are already stalled anyway; perhaps that is why the Rugeley wind penalty (Figure 3) seems to flatten out for winds beyond about 12 m/s.

Although Figure 3 seems to suggest a clear superiority for the Grootvlei arrangement, it should be kept in mind that the Grootvlei pressure drop is more than twice that at Rugeley, and this fact is no doubt responsible for much of the difference shown. If Rugeley had the same pressure drop as Grootvlei, the stall effect would tend to appear at 8 m/s instead of 5 m/s.

It seems very clear that special means should be developed to accomplish loss-free entrance of oblique flows into heat exchangers for dry cooling towers. In that environment, obliquity is poorly controlled, especially because of wind. Therefore, designs to provide easy turning could be important not only to reduce wind effect, but to improve basic performance (through a reduction of $\beta$, in effect).

## Effects of Exit-Flow Distortion.

Especially when wind acts on a tower, the exit flow does not simply match its static pressure to the ambient value at the exit lip, as one would customarily assume in calculating draft. Studies of plume behavior [29] are of little help here, because they are usually concerned with the development of the plume after it leaves the tower. More to the point are recent studies by Ernst [30] which describe observations at tower exits in the presence of wind, and discussions of cold inflow by Jorg and Scorer [31]. Typical exit velocities are about 3 m/s; therefore winds will sometimes be weaker, but are usually stronger than the outflow. Consequently, exit flows of cooling towers are very complex and ill-understood.

In [30] it is reported on the basis of observations of evaporative towers that a degree of cold-air intrusion at the top of the tower will take place at any wind speed, and that from, say, 2 to 10 m/s there is an increasingly large stationary eddy system which partially blocks the tower. In the lower part of this speed range, from 2 to 5 m/s, the flow is unsteady, emerging in puffs. Beyond 10 m/s, strong side lobes or vortices are formed with very rapid mixing.

It is premature to try to explain or predict these effects. However, two physical phenomena can be inferred: (a) The emerging flow must have a total pressure capable of withstanding some fraction of wind total pressure. Thus, for wind beyond about 3 m/s, it is unlikely that static pressure of flow and wind could match at the tower top. Instead, the exit flow will need to acquire more dynamic pressure. This it can do only by narrowing its exit area; in other words, by separating from the tower walls. Eq. (9) makes clear that such a narrowing of $A_E$ would be equivalent to an increase of $\beta$ (the duct-loss coefficient) so far as loss of performance is concerned. Clearly, this effect can be a powerful contributor to the losses described in Figure 3. (b) Typically, the emerging flow is just barely statically stable against cold inflow. Suppose there is no wind, and the exit is cylindrical, with a velocity of 3 m/s. If the static pressure of the flow is matched to ambient at the exit, but the exit air temperature is 20C above ambient, then the total pressure in the tower would exceed the static pressure of stagnant ambient air at that level only for the top 7 m of the tower. In other words, if a "finger" of cold ambient fluid could penetrate below 7 m from the top of the tower, it would continue to spill down to the heat exchangers. In a wind situation, with an exit diameter 10 times that critical depth, it is easy to imagine such occurrences, and perhaps the "puffing" phenomenon is related to this static instability to finite disturbances. Such effects would be opposed by strong mixing in the tower-flow boundary layer, and hence one may argue the importance of keeping a full transverse profile of velocity in the tower.

In summary, it would seem that exit losses due to wind could be minimized by effords to deflect the wind upward, to prevent its full dynamic pressure being brought to bear on the exit flow, and by efforts to achieve a fully-developed turbulent velocity profile in the upper part of the tower.

It should be emphasized that all design advances to reduce losses in a dry cooling tower, whether due to exit-flow phenomena or heat-exchanger and entrance behavior, will have the effect of making the tower flow more securely one-dimensional, and will lead ultimately to the option of low towers, which will be aesthetically acceptable, and have lower construction costs than present designs.

## HEAT REJECTION BY THERMAL RADIATION

A final, more speculative prospect for dry cooling is the release of waste heat by long-wave radiation directly to the atmosphere; in effect to the water vapor in the atmosphere. (Direct thermal radiation to space is not possible, because of the opacity of the atmosphere in that spectral range.) This possibility is discussed in [3] and [32]. We consider a surface that is black for thermal radiation but perfectly reflecting for sunlight. Ordinary white paint would be good enough, perhaps. This surface is placed in thermal contact with hot water from a condenser. With solar imput blocked, the surface will reject heat (somewhat as if to the night sky). We may assume an emissivity of the atmosphere of about 0.69 to calculate thermal radiation to the surface. The result would be about 80 Btu/ft$^2$-hr. if the atmosphere is at 50F. If the surface is at 100F, it will radiate about 170 Btu/ft$^2$-hr. A net rate of heat rejection of 90 Btu/ft$^2$-hr would be achieved, which would require a surface area of about 2 1/2 mi$^2$ to serve a typical 1000 MWe nuclear power plant rejecting 6.6'10$^9$ Btu/hr.

While 2 1/2 sq. mi may seem excessive, it should be noted that a cooling pond for the same service would be comparable, and the environmental impact would be the ultimate ideal; dispersed, and with no convection or water consumption. The average height of water vapor in the atmosphere is about 1 mi, so the atmospheric heat sink is itself widely dispersed on the scale of miles. Especially for situations where pond storage is feasible or needed, this radiative mechanism should be studied; perhaps to augment some other type of cooling system.

In view of the national interest in solar energy, perhaps a cooling system of this type should be called R.S.P. (Reverse Solar Power).

## CONCLUDING REMARKS

In this paper, we have noted the present reluctance to adopt large-scale dry cooling for power plants, mainly owing to high cost, sensitivity to high ambient temperatures and to atmospheric fluctuations, and to a lack of compelling aesthetic merit. We have then inquired into the prospects for technical improvement or innovation which might lead to more favorable evaluations.

Certain system considerations may prove important in this regard; wet peaking, cold storage, gas-turbine power cycles, and small plant size would all tend to assist the introduction of dry cooling. We have emphasized, however, the purely technical features of dry towers, especially of natural draft, and considered the scope for improvement.

It is suggested that more refined aerodynamic design, essentially to make the various flow elements better conform to the assumptions of one-dimensional duct flow, could reduce tower dimensions (most critical for cost) by the order of 10 percent, at the same time eliminating or even reversing wind effect which can be responsible for about 1 percent loss of peak power production. Some of the technical indications are; oblique approach to heat exchangers should be avoided, and loss-free entrance should be devised for such obliqueness as proves necessary, or likely to occur because of wind; external heat exchangers should probably be avoided; means should be devised to prevent wind dynamic pressure from exerting a direct effect on the exit flow; and strenuous efforts should be made to achieve a flat velocity profile in the tower, in order to minimize cold inflow from the tower top.

All these avenues of improvement recognize that cooling tower flows have been very loosely controlled (to an aerodynamicist's taste) and there is much room for improvement. The potential payoff for improvements of conventional towers is worthwhile, but perhaps not startling. The real payoff will be indirect, in learning how to make towers that are low and wide, but still keep their one-dimensionality. Then costs and benefits will both improve to the point that dry cooling may well have a different level of appeal to the industry.

A more speculative possibility for dry cooling improvement can be seen in the possible use of radiative release to atmospheric water vapor, and dry cooling for power plants is just one of many technologies that would be transformed by the invention of a self-cleaning ultra-fine heat exchanger surface!

## ACKNOWLEDGEMENT

Studies upon which this paper was based were supported by ERDA, through grant No. EY-76-S-02-2924.*000 and by NSF, through grant GI-34776.

## REFERENCES

1. J.E. Carson, "Atmospheric Impacts of Evaporative Cooling Systems", Argonne Nat'l Lab. Rep. ANL/ES-53, Oct. 1976.

2. F.K. Moore, "Regional Climatic Effects of Power-Plant Heat Rejection", Atm. Env, Vol. 10, pp. 806-811, Oct. 1976.

3. F.K. Moore, "Dry Cooling Towers", Adv. Heat Transfer, 12, Academic Press, pp. 1-75, (1976)

4. S.R. Hanna and F.A. Gifford, "Meteorological effects of energy dissipation at large power parks", Bull. Am. Meteorol. Soc., 56(10): 1068-1076.

5. J.P. Rossie and W.A. Williams, Jr., in "Dry and Wet/Dry Cooling Towers for Power Plants", (R.L. Webb and R.E. Barry, Eds.) ASME Publ. HTD 6, 49 (1973).

6. B.C. Fryer, "A Review and Assessment of Engineering Economic Studies of Dry Cooled Electrical Generating Plants", Battelle Pac. N.W. Lab. Rep. BNWL-1976, UC-12, Mar. 1976.

7. "Heat Sink Design and Cost Study for Fossil and Nuclear Power Plants", Prepared by United Engineers and Constructors, Inc., for Div. Reactor Res. and Dev., U.S. AEC, WASH-1360, Dec. 1974.

8. P.J. Christopher and V.T. Forster, Proc. Inst. Mech. Engr. 184, Pt 1, No. 11, 197, 1 (1969-70).

9. N.T. van der Walt, L.A. West, T.J. Sheer, D. Kuball, "The Design and Operation of a Dry Cooling System for a 200 MW Turbo-Generator at Grootvlei Power Station, South Africa", Presented at 9th World Energy Conference, Detroit, Sept. 22-27, 1974.

10. F.K. Moore, K.E.Torrance, et.al., Probable Loss of Production of Three Locations, Due to Temperature Changes, Wind, and Inversions. Memo, ERDA Grant EY-76-S-02-2023.*000, 11 Nov. 1976.

11. Goecke et al., "Die Kondensations Anlage des 150-MW Blocks Im Kraftwerk Ibbenburen der Preussag A.G." May 1969.

12. J. Heeren and L. Holly, Proc. Am. Power Conf. 32, p. 579, Ill. Inst. Techn. (1970).

13. R.C. Norton, W.J. Westre and G.L. Larsen, "Dry Cooling Design Characteristics of a Large Power Plant", Proc. Am. Power Conf. 37, p. 591, Ill. Inst. Tech., Chicago. (1975).

14. J.M. Krase, D.C. Morse and T.W. Schoene, Proc. Am. Power Conf. 34, p. 512, Ill. Inst. Techn. (1972).

15. E.C. Guyer and M.W. Golay, "Evaluation of Combined Thermal Storage Pond and Cooling Tower System," Trans. Amer. Nucl. Soc., 22. 509 (1975).

16. H.-H. von Cleve, "Comparison of Different Combinations of Wet and Dry Cooling Towers", ASME Publ. 75-WA/Pwr-10, 1975.

17. M.W. Larinoff and L.L. Forster, "Dry and Wet-Peaking Tower Cooling Systems for Power - Plant Applications", ASME Publ. 75-WA/Pwr-2, 1975.

18. W.J. Yang and D.W. Clark, Int. J. Ht Mass Transfer. 18, p. 311 (1975).

19. M.W. Larinoff, in "Dry and Wet/Dry Cooling Towers for Power Plants", (R.L. Webb and R.E. Barry, Eds.) ASME Publ. HTD 6, 57 (1973).

20. M.W. Robertson and L.R. Glicksman, in "Dry and Wet/Dry Cooling Towers for Power Plants", (R.L. Webb and R.E. Barry, Eds.) ASME Publ. HTD 6 139 (1973).

21. R.G. Barile, "Turbulent Bed Cooling Tower", EPA Rep. EPA-660/2-75-027, Corvallis, O., June 1975.

22. J.P. Rossie and E.A. Cecil, "Research on Dry-Type Cooling Towers for Thermal Electric Generation", Part I, Water Pollution Control Research Series 16130EES11/70, Environmental Protection Agency, Nov. 1970.

23. C. Roma, Proc. Am. Power Conf. 35, 526, Ill. Inst. Techn. (1973).

24. C.C. Ndubizu, "Influences of Component Cost Changes on the Optimum Design of Large Natural Draft Dry Cooling Systems", Cornell Energy Program Rep. EPR-76-3, Ithaca, N.Y. (1976).

25. F.K. Moore, "Equations for Estimating Performance Losses of Natural-Draft Dry Cooling Towers", Cornell Energy Program Rep. EPR-76-4, Ithaca, N.Y. (1976).

26. F.K. Moore and C.C. Ndubizu, "Analysis of Large Dry Cooling Towers With Power-Law Heat Exchanger Performance", Journal of Heat Transfer, p. 345-352, Aug. 1976.

27. D., Kuchemann, and J. Weber, Aerodynamics of Propulsion, McGraw-Hill Book Co., Inc. New York, N.Y. 1953.

28. D.C. Baxter, "Flow Losses in Heat Exchangers with Oblique Flow Ducts-A Summary of Available Design Information," Technical Rept. No. 25, Department of Mechanical Engineering, Stanford University, June 1955.

29. G.A. Briggs, "Plume Rise", AEC Critical Review Series, TID 25075, U.S. N.T.I.S. (1969).

30. G. Ernst, "Cooling Towers, Design and Plume Behavior", Seminar of Int. Cen. Ht. Mass. Transf. (Dubrovnik) 1975.

31. O. Jorg and R.S. Scorer, "An Experimental Study of Cold Inflow into Chimneys", Atm. Env. 1 , pp. 645-654, (1967)

32. G.A. Tsongas, C.A. Depew, and A. Hertzberg, Proc. Combined Ann. Thermal Pollution Conf. 2nd: Bien. Hydraulics Conf. 8th, Washington State Univ., Pullman, Washington, pp. 417-432, October, 1971.

33. D.R. Pratt, "Compatibility of Ammonia with Candidate Dry Cooling System Materials", Battelle Pac. N.W. Lab. Rep. BNWL-1992, UC-38, April 1976.

# TABLE 1. PERFORMANCE PARAMETERS

| | |
|---|---|
| Q (heat rejection rate) | 1.6 $10^5$ Btu/sec |
| $P_W$(ratio, water pumping power/Q) | 0.001 |
| I (ITD) | 40°F |
| P/I (approach/I) | 0.6 |
| s (tower aspect ratio - natural draft) | 1/703 |
| ambient sea-level air: | $p_a$ = 2116 psi<br>$T_a$ = 547°R |

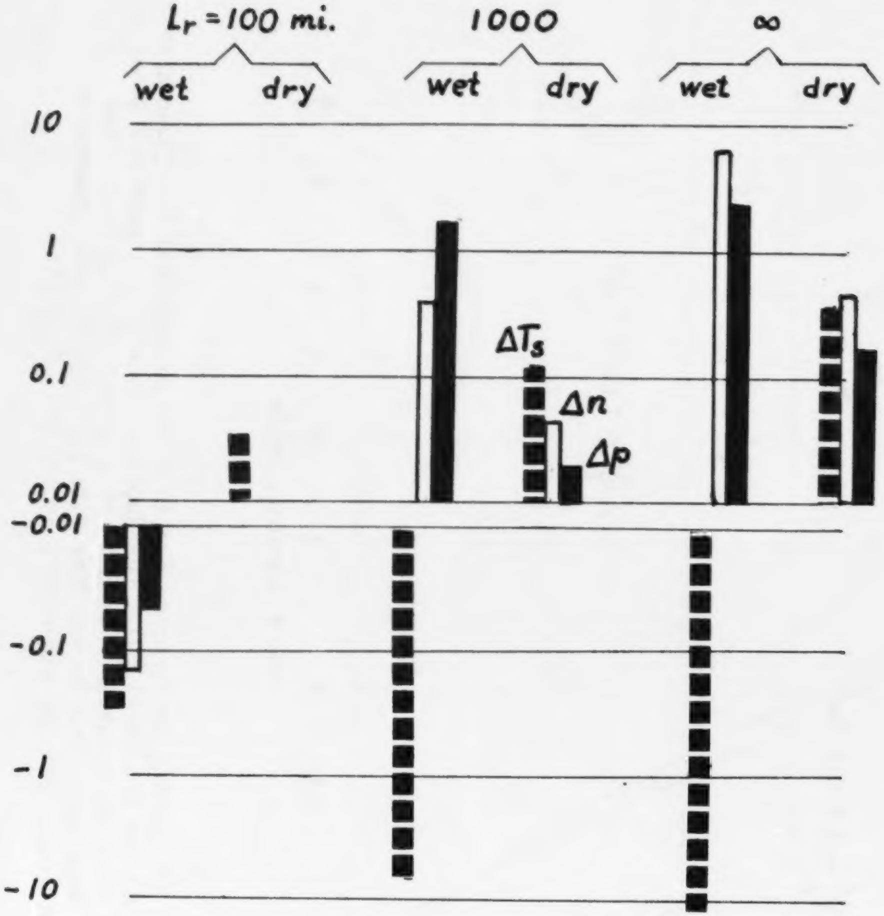


Figure 1: Estimated average increases of regional surface temperature (ΔTs), cloud cover (Δn) and precipitation rate (Δp) if heat is rejected at 1% of solar imput (9 MW/mi$^2$) in a region of windward scale $L_r$. Climate is that of Yuma, Ariz. Adapted from [2]. The values of Δnand Δp for dry towers are too small to show, when $L_r$=10 mi.

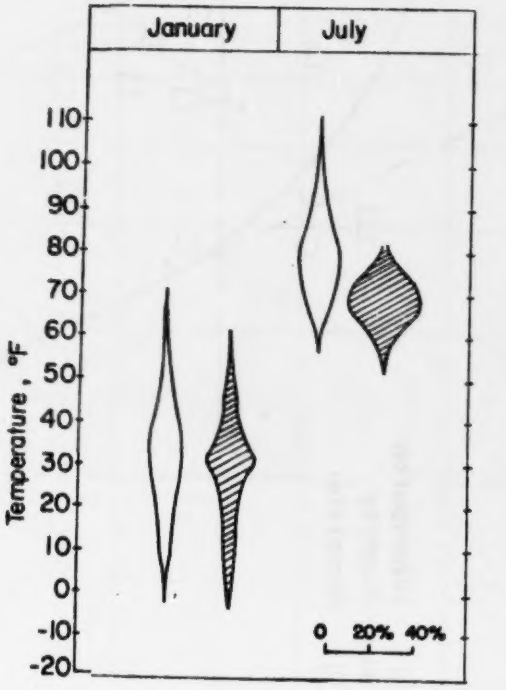


Figure 2: Long term probabilities of dry-bulb (open shapes) and wet-bulb (shaded shapes) temperatures at Kansas City, Mo. Scale is fraction of time that temperature is in a 4°F interval. Excerpted from [3].

FKM

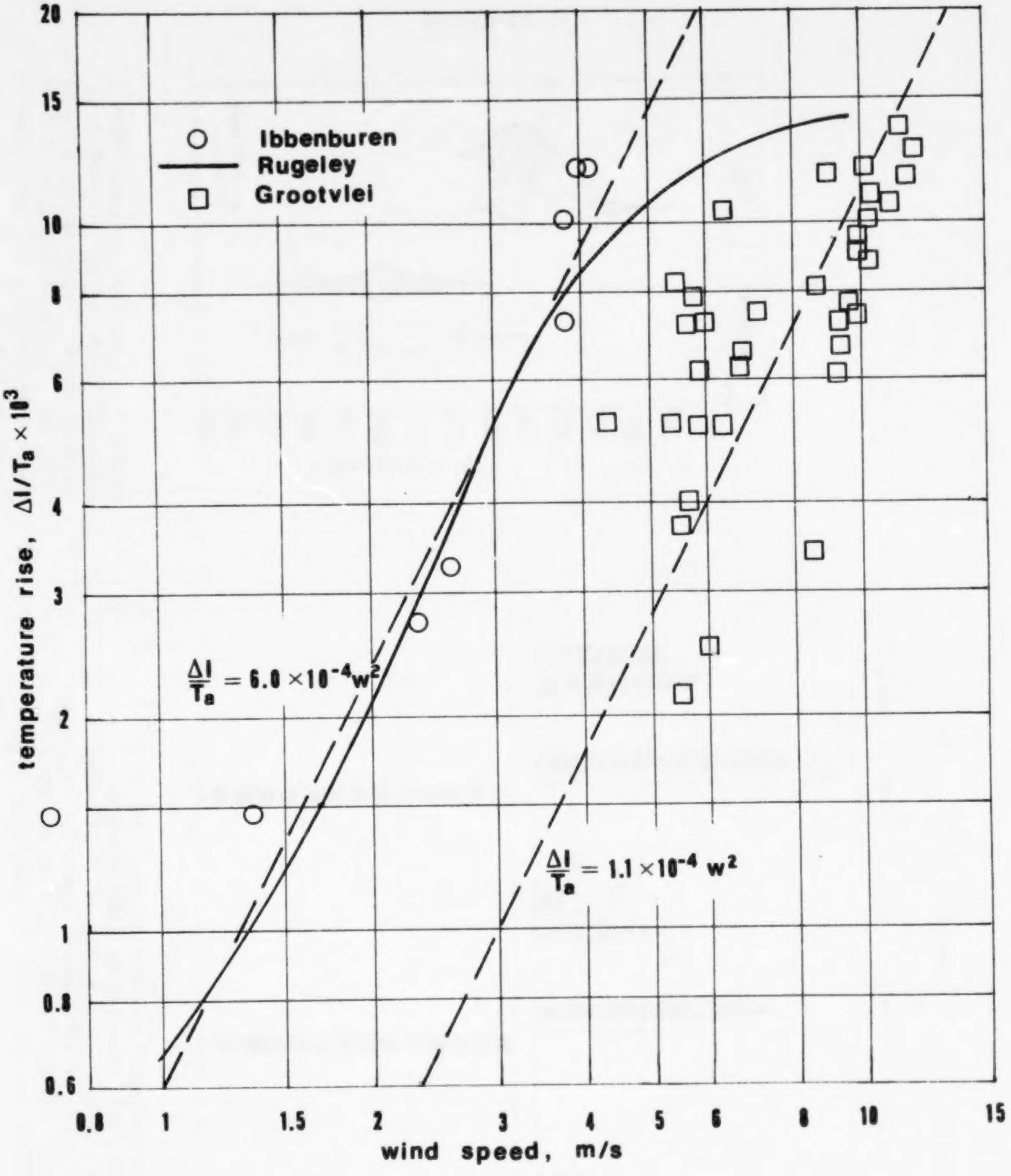


Figure 3: Loss of cooling performance due to wind, as reported for Ibbenburen [11], Rugeley [8] and Grootvlei [9]. For Rugeley, data points were not given - only the solid line was reported. Wind is at a height of 10 m (requiring correction for Rugeley). One dashed line fits both Rugeley and Ibbenburen, except for high winds, and the other fits Grootvlei. From [25].

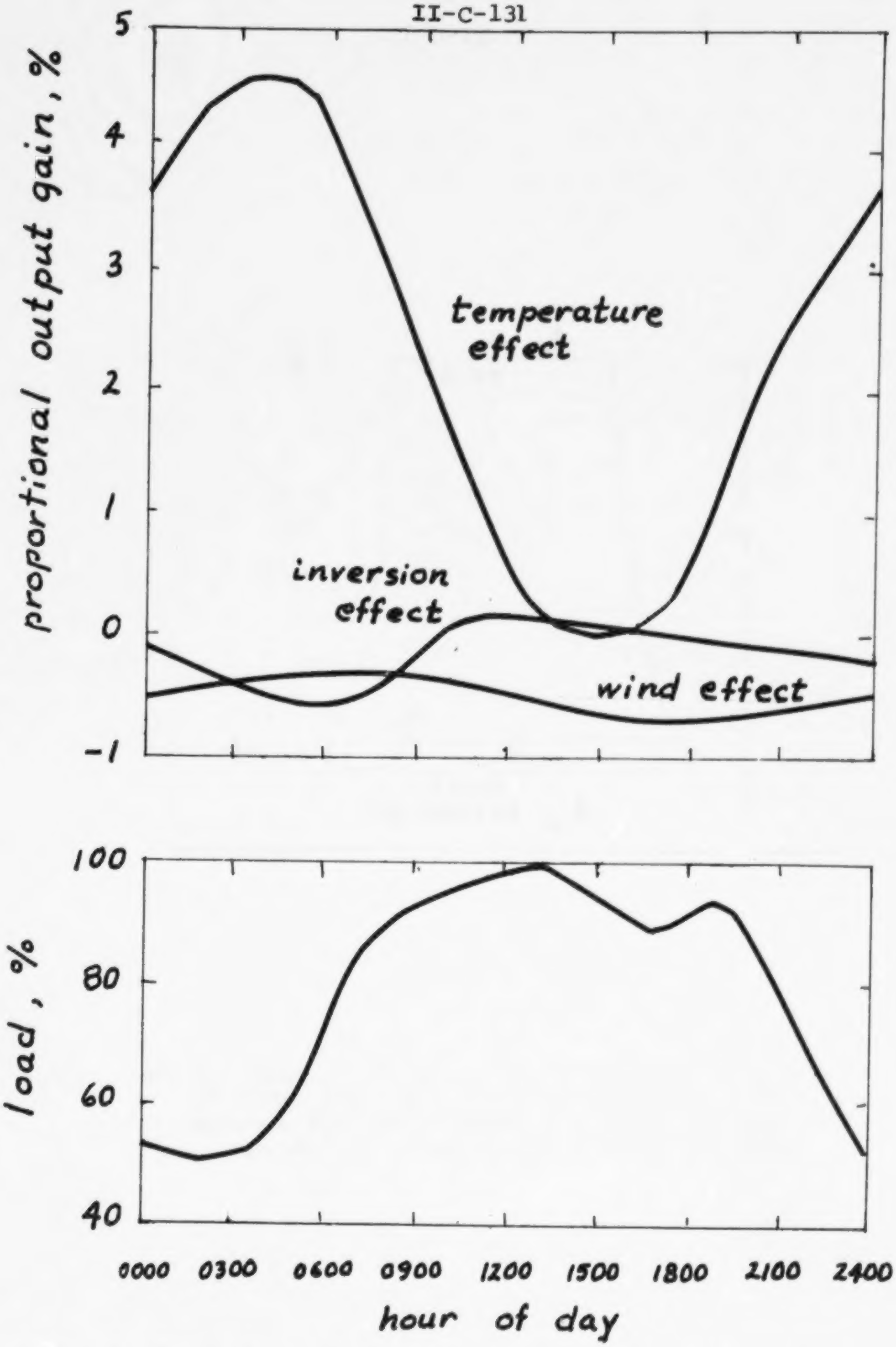


Figure 4: Proportional diurnal changes of output of a dry-cooled power plant, due to long-term averaged diurnal variations of temperature and wind, and the occurrence of inversions, as calculated in [10] for Las Vegas, Nev. in July. Curves are based on Eq. (17), as applied to a Grootvlei type of tower, for which wind effect is quite small. The corresponding daily demand curve is shown for comparison.

162<

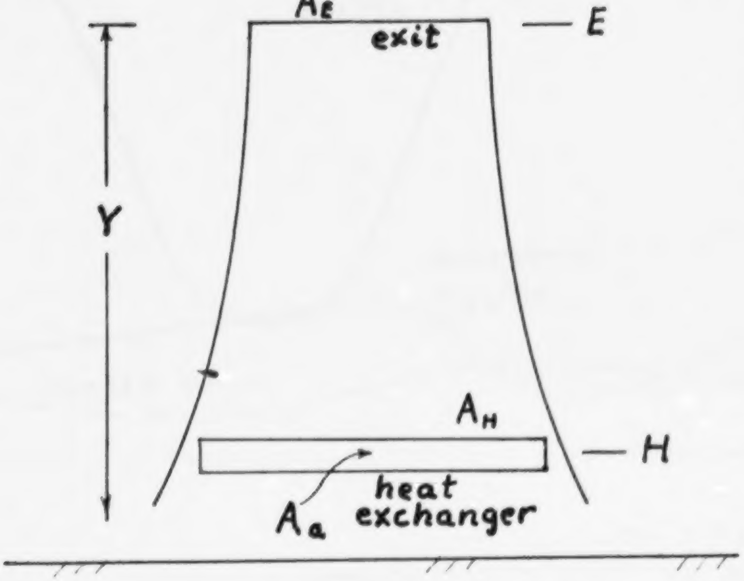

$A_E$
exit
E
Y
$A_H$
H
heat exchanger
$A_a$

Figure 5: Sketch of cooling tower. $A_H$ refers to the cross-sectional area of the tower base, while $A_a$ refers to the heat exchanger. The heat exchanger configuration is not necessarily as sketched.

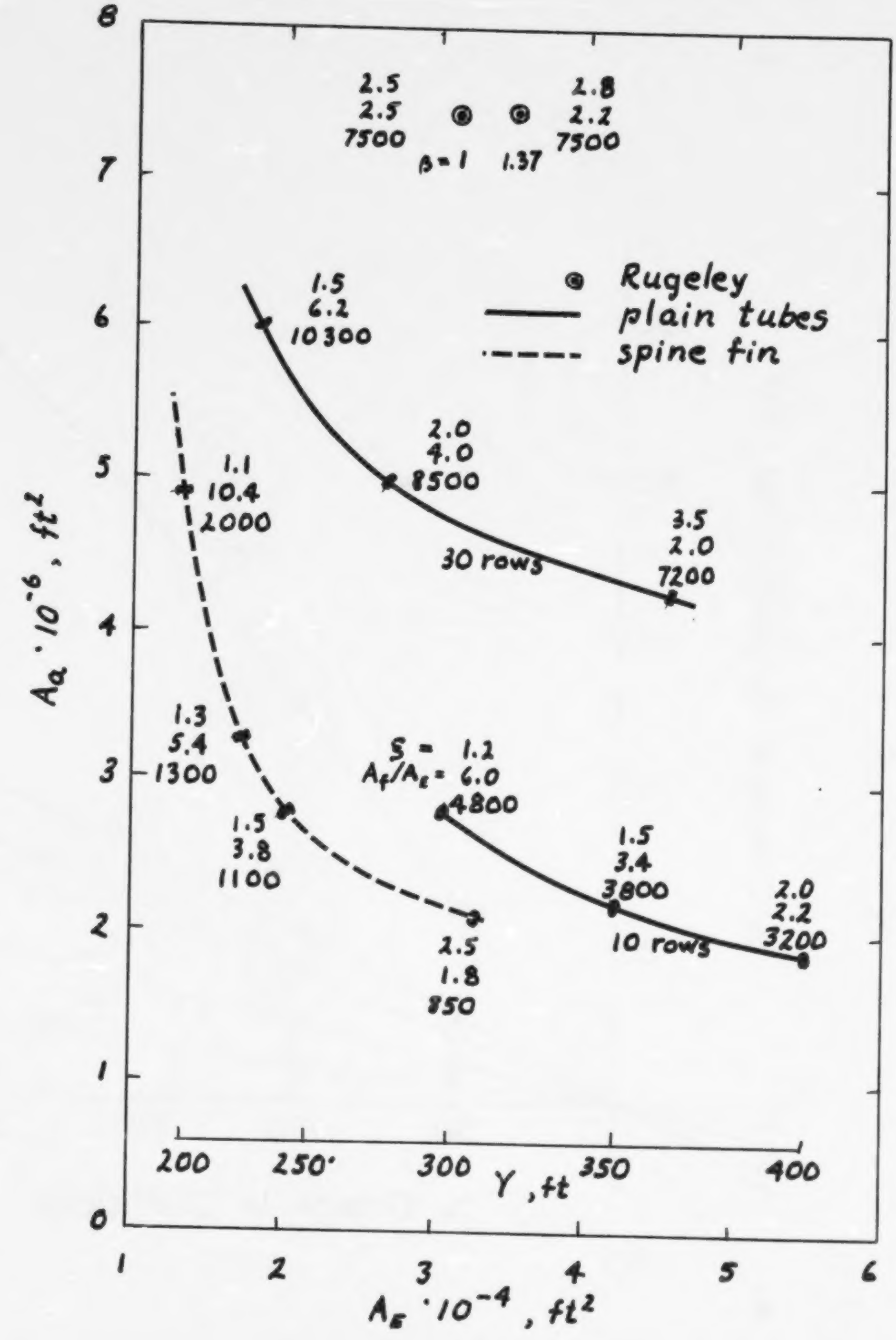


Figure 6: Air-side heat-transfer area as a function of tower exit area for natural-draft dry towers with particular heat-exchange surfaces. Because tower shape $Y/\sqrt{A_E}$ is fixed, abscissa can be either Y or $A_E$. The "plain tube" cases perhaps correspond to [23]. Shown at each point are ξ, $A_f/A_E$ and volume of material in the heat exchanger. Excerpted from [3].

164<

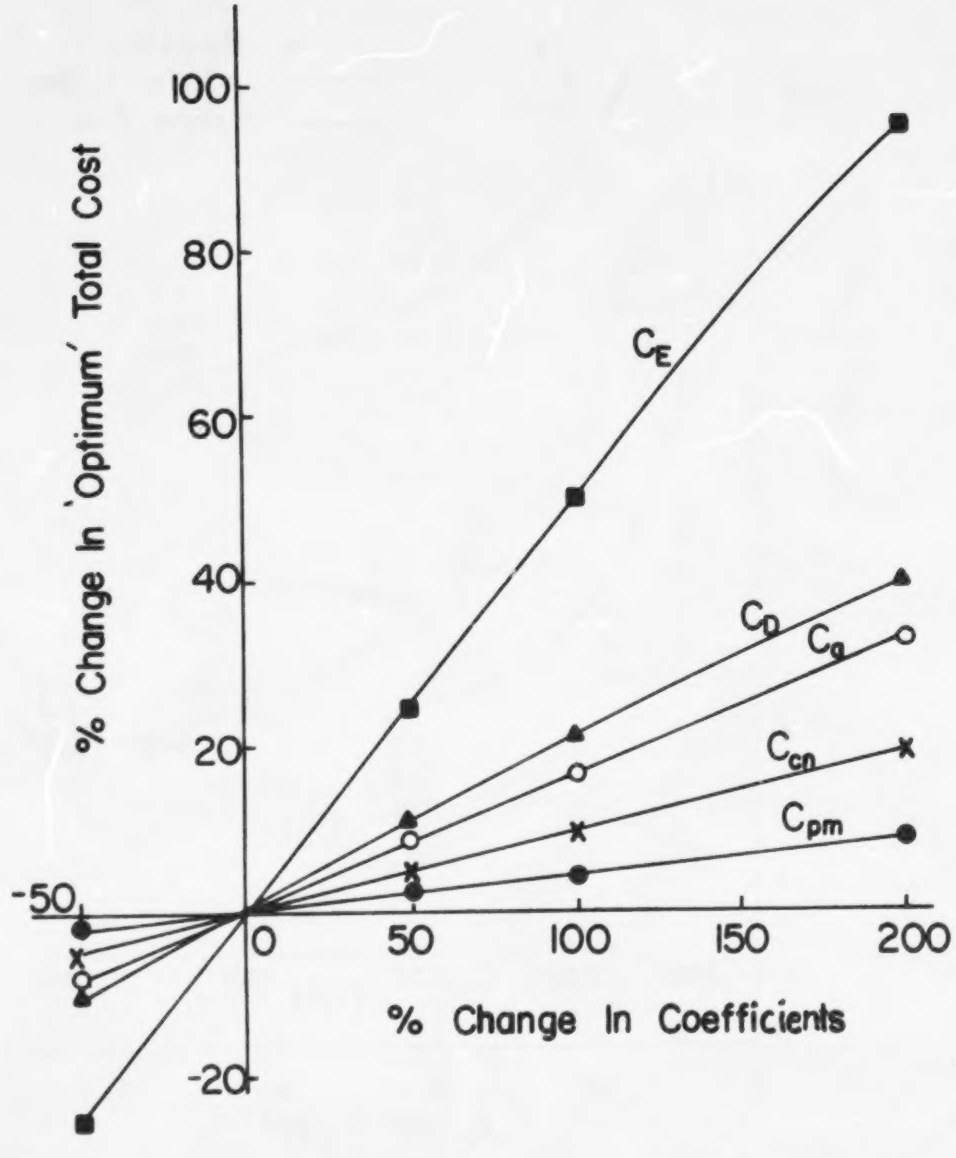


Figure 7: Effects on an optimized tower cost, as cost coefficients for various elements are changed. $C_E$ and $C_a$ refer to exit area and heat-exchange area, $C_D$ refers to diameter of header piping, and $C_n$ and $C_{pm}$ refer to condenser and pump sizes. From [24].

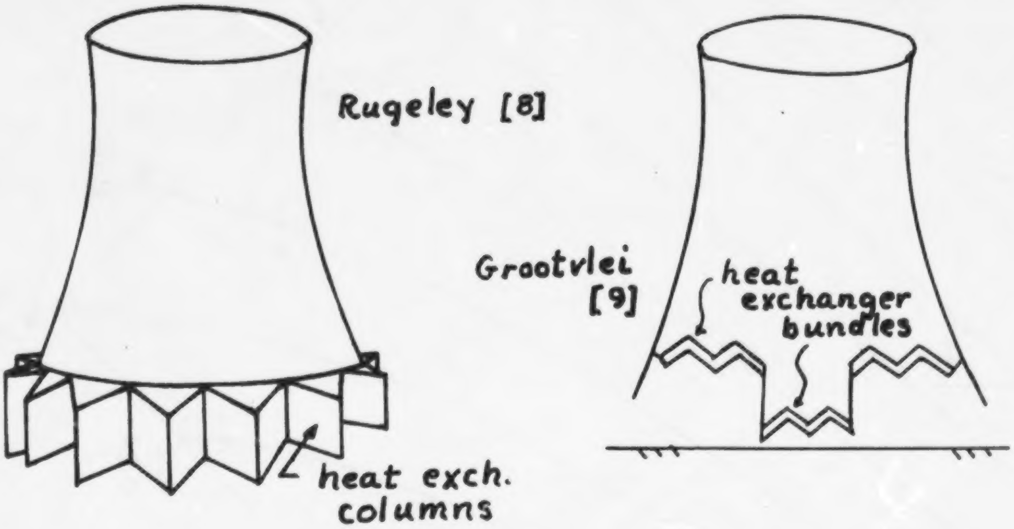

Rugeley [8]
heat exch. columns
Grootvlei [9]
heat exchanger bundles

Figure 8: Sketches of the external, vertical column arrangement of the Forgó heat exchangers at Rugeley [8] and Ibbenburen [11], and of the internal, "roof-top" array at Grootvlei [9].

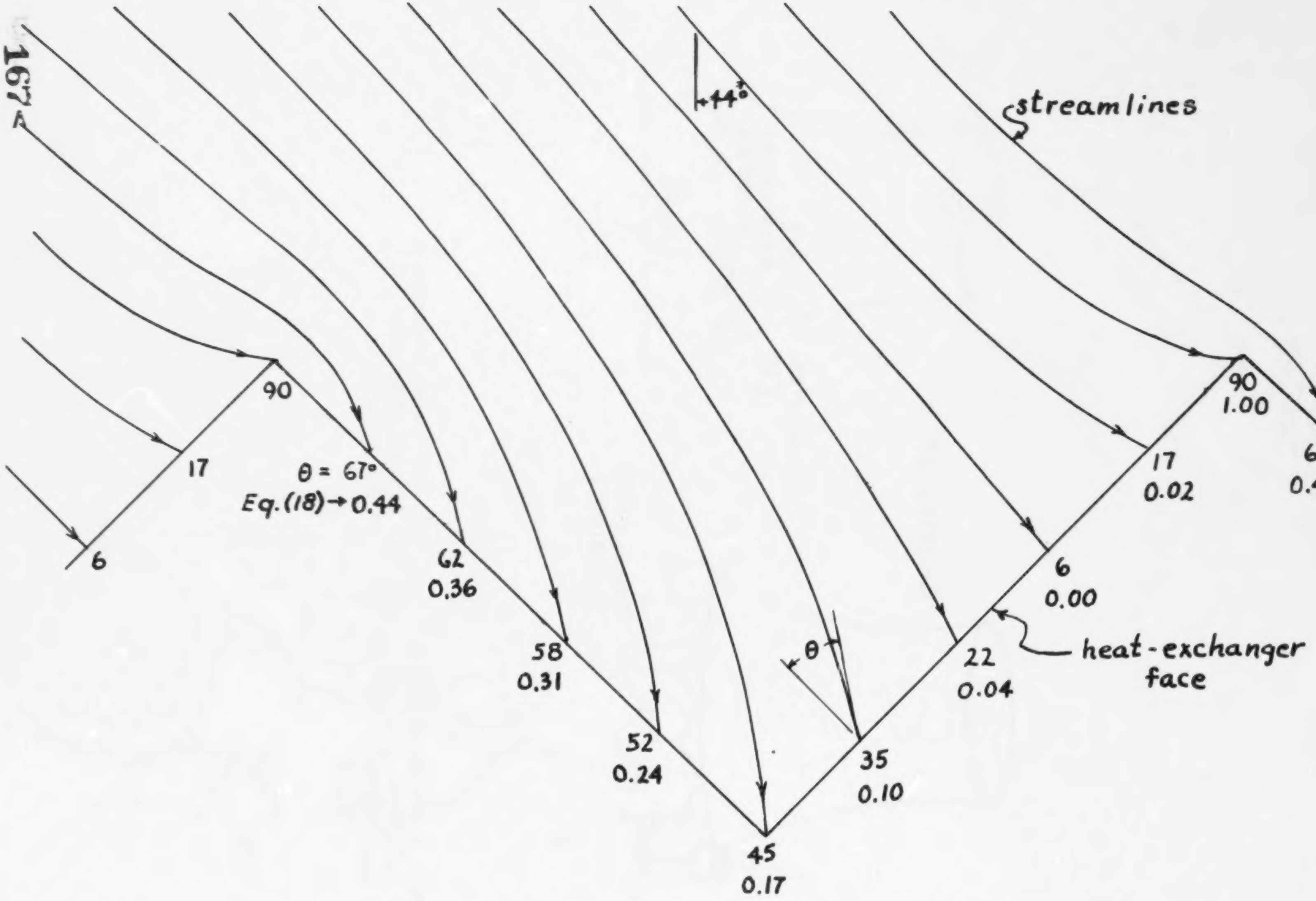

streamlines
+44°
90
17
6
θ = 67°
Eq.(18) → 0.44
62
0.36
58
0.31
52
0.24
45
0.17
35
0.10
θ
22
0.04
heat-exchanger face
6
0.00
17
0.02
90
1.00
67
0.44

Figure 9: Calculated potential streamlines approaching a repeating delta array of heat exchangers. The heat-exchanger pressure drop is assumed so large that normal velocity is constant along all faces. The flow approaches with an initial obliqueness of 44°. Obliqueness variation along each face is shown, together with an estimate of corresponding pressure loss.

omit

# "WATER CONSERVATION AND WET-DRY COOLING TOWERS IN POWER PLANT SERVICE"

By: M. W. LARINOFF
VICE PRESIDENT
HUDSON PRODUCTS CORPORATION
HOUSTON, TEXAS

Time and circumstance is bringing about the "marriage" of the wet tower and the dry tower into a single, power plant type, cooling system that represents the best of both towers. It has the water conservation features of the dry tower and the low capital cost of the wet tower. The "time and circumstance" are that not all desirable power plant sites have 20 million gallons of makeup water available every 24 hours for a 1000MW nuclear electric power generating unit. The competition for available water supplies between agriculture, manufacturing and electric utilities is becoming apparent in some areas of the country.

Dry and wet-peaking tower cooling systems can be designed to consume any quantity of makeup water -- from zero to 100% of what a wet cooling tower needs. The larger the water consumption, the lower the capital cost of the steam condensing/water cooling system. These systems are all tailored to serve the conventional, low exhaust pressure, steam turbine generator unit. There is no new technology involved in this "marriage" -- just a need to conserve water.

There are several basic wet/dry tower water-flow schemes that can be used. They each have their own advantages and shortcomings. Thermal performance characteristics are essentially the same for all. Long term maintenance and operating costs are affected. The significant differences of alternative designs will be examined and discussed.

The paper will also review some of the more recent published work done by others in this field. Their conclusions and findings will be discussed in the light of the future role that this power plant heat-sink may have in easing expansion at existing plant sites and in the location of new sites.

MWL/bm
12-28-76

9-45-32

II-C-139

# MODIFICATIONS TO ONCE-THROUGH COOLING WATER DISCHARGE STRUCTURE TO ACHIEVE ENTRAINMENT MIXING AND LATERAL TRANSPORT OF THERMAL PLUME

D. E. Miller
W. A. Sim
C. L. Buck
Alabama Power Company
Birmingham, Alabama U.S.A.

## ABSTRACT

Alabama Power Company has recently completed structural modifications to the cooling water discharge structures for the Gaston Steam Electric Generating Plant* Units 1-4 (250 MW each) located on the Coosa River at River Mile 435.7 near Wilsonville, Alabama. These modifications were designed to increase the velocity and reorient the direction of the discharged condenser cooling water so as to enhance entrainment of ambient waters, thus reducing plume temperatures, while maintaining a bouyant plume with sufficient momentum to carry the discharge a sufficient distance downstream.

The reasons for this modification were essentially two-fold. First, Plant Gaston has historically been plagued by recirculation from condenser discharge to inlet due to the close proximity of the intake and discharge structures. Additionally, the NPDES permit requires improvement of the thermal regime in the vicinity of the plant. Alabama Power Company engineers feel that the modifications successfully accomplish these objectives and expect an increase in generating plant efficiency due to the reduction of recirculation and thus intake temperature.

This project has involved several phases of work. First, extensive thermal monitoring was conducted in the river to evaluate the extent to which the river was affected by the unmodified thermal plume behavior. Such monitoring established that with a still river, a stratified plume developed bank-to-bank and extended considerable distances up and downstream. Behavior of the plume was also studied when the river was flowing as a result of upstream hydroelectric operations.

Next, analytical simulations were made to evaluate various discharge jet configurations and define the resulting thermal plume. It was concluded that it was possible to utilize a surface discharge to produce the desired downstream movement and entrainment.

---

*The E. C. Gaston Plant of Southern Electric Generating Company is jointly owned by Alabama Power Company and Georgia Power Company and operated by Alabama Power Company.

Finally, engineering drawings and construction methods were developed which allowed the modifications to be made without necessitating the removal of the generating units from service.

This presentation will describe this project and will present results of thermal studies which have been conducted subsequent to the modifications.

## INTRODUCTION

Gaston Steam Electric Generating Plant, operated by Alabama Power Company, is located on the Coosa River at Wilsonville, Alabama. River flows at the Gaston Plant are controlled by Logan Martin Dam 22 miles upstream and Lay Dam 14 miles downstream. At the plant site, the river is approximately 550 feet wide and 55 feet deep along its centerline. Flows in the river vary widely throughout the year, normally reaching a maximum in early Spring and a minimum in late Summer and Fall. Although the average river flow at the plant is 13,800 cfs, the average monthly flows during the warmer low flow periods are 4,000 and 5,000 cfs.

There are five steam-electric generating units at the Gaston Plant. An 880 MW unit operates on closed-cycle cooling and four 250 MW units operate on once-thru cooling. Water is withdrawn from Yellowleaf Creek, which joins the Coosa River about one-half mile upstream of the plant discharge structures. There is one discharge structure for Units 1 ana 2 and a separate structure 235 feet downstream for Units 3 and 4. Prior to the modifications, the structures were oriented so as to direct the discharge toward the opposite bank of the river and slightly upstream, as shown on Figure 1. During periods of low flow and intermittent hydroelectric operations, a recirculation problem was created causing heated discharge water to flow upstream to Yellowleaf Creek and from there to be recirculated through the plant. The result of this recirculation was to cause a surface temperature during the warmer months greater than 90°F across the river and increased back pressure on Units 1 through 4 due to higher intake temperatures.

The Environmental and Technical Services Department at Alabama Power Company reviewed the thermal problem in light of the energy penalties associated with higher back pressures and on-going negotiations with the Environmental Protection Agency relative to the issuance of an NPDES Permit on Plant Gaston. After the situation was analyzed, a proposal based on analytical model studies was presented to EPA Region IV to improve the thermal regime in the vicinity of the plant which included modification of the discharge structures. This proposal was accepted and an NPDES Permit issued on Plant Gaston which required discharge structure modifications and contained appropriate thermal limitations.

## PREVIOUS CONDITIONS

Generating Units 1 thru 4 at Plant Gaston withdraw water from the Coosa at a total rate of about 1,300 cfs and a condenser rise of about 14 to 20°F depending upon pump operation and plant load. Evaluations of plant log data, measurements of temperatures in the river, and infrared imagery have shown recirculation at Plant Gaston to be a problem. This recirculation results in an intake temperature higher than that which would otherwise exist. This higher intake temperature causes the plant to operate at a lower efficiency and results in further elevation of discharge temperatures which reflect the higher intake temperature plus the additional heat due to the decrease in plant efficiency.

Results of thermal sampling conducted during September, 1973, in the vicinity of Plant Gaston are shown on Figure 2. These figures illustrate the ability of the thermal plume to move several miles upstream. Generation values shown for upstream Logan Martin Dam, for the sample day and the day prior, indicate that the intermittent river flow is insufficient to prevent the formation of the plume.

The United States Geological Survey operates a water quality monitoring station on the Coosa River near Childersburg about ten miles upstream from Plant Gaston. Daily temperatures recorded from this gage are considered to be unaffected by the plume and have been analyzed for the period May through October, 1969-1974.1/ A cumulative frequency plot of daily temperatures has been prepared from this data. Likewise, daily averages of the Plant Gaston intake temperatures have been analyzed and presented in the form of a cumulative frequency plot covering the period May through October, 1970-1974. These plots are both shown on Figure 3. The difference in the temperatures, for a specific occurrence frequency, is indicative of recirculation of plant discharge water.

It is noted that while 5°F is a typical difference in these temperatures, measurement techniques and sampling methods may produce some of this difference so that these values cannot be interpreted as absolute measurement of recirculation. However, independent field measurements of temperature in the vicinity of the gage correlate overall to about 1°F with the U.S.G.S. record which tends to verify the comparison of the intake and Childersburg temperature frequencies.

Results of a regression analysis using 1972 data show that heavier releases from Logan Martin reduce the difference between the intake and Childersburg gage temperatures and result in a reduction in the recirculation, as shown in Figure 4. However, it is also concluded that stream flow during the warm low-flow months is insufficient to remove the recirculation effects through increased operation of Logan Martin.

## ANALYSIS OF MODIFICATIONS TO THE DISCHARGE STRUCTURE

The Gaston Plant utilizes two separate discharge structures. One structure serves Units 1 and 2 while the second serves Units 3 and 4. Reduction of pump log temperature data from 1970 through 1974 indicated that condenser rises of 14°F to 21°F were experienced 90% of the time (Figure 5). Condenser water leaves the plant in two closed conduits at a velocity of about 5' per second. This water subsequently discharges into an open channel section prior to its discharge into the river. Before the modifications to the outfall structure, these open sections were designed to dissipate the velocity head. Assuming complete transition, the velocity reduced to approximately 1.4' per second.

1/"Water Resources Data for Alabama, Part 2, Water Quality Records" United States Department of the Interior Geological Survey.

Evaluation of the temperature and velocity associated with existing discharge structure produced a Froude Number less than 1, which supported previous thermal measurements showing a cold water wedge extending into the open channel portion of the structure. This low Froude Number resulted in the formation of a very bouyant plume that had the capability of moving significant distances upstream in a matter of hours. The upstream movement of the plume was further facilitated by the open channel sections which were oriented with respect to the river such that the thermal discharge was directed slightly upstream toward the mouth of Yellowleaf Creek.

An analytical simulation of the thermal/hydraulic behaviour of the modified discharges in the vicinity of the plant was conducted. The model used in this analysis was a "Three Dimensional Heated Surface Discharge Computation" model by Stolzenback, Adams, and Harleman, published by EPA in January, 1973.

It was initially assumed that the objectives of the proposed modifications to the discharge structures, i.e. elimination of recirculation and reduction of receiving water temperatures, could be accomplished by adequately affecting the near field region. The temperature distribution induced in the receiving water by a heated discharge is determined by the characteristics of the discharge structure and by the local ambient heat transfer processes. Close to the point of discharge the momentum of the discharged water creates jet-like mixing of the heated and ambient water. Within the "near field" region the temperature and velocity of the discharge decrease because of dilution by entrained water. The magnitude and extent of the dilution is determined primarily by the nature of the initial discharge flow, its submergence, velocity, dimensions and temperature rise above ambient. Mixing increases with increasing discharge momentum and decreases with increasing temperature rise. The greater the submergence of the discharge below the water surface, the lower the temperature rise at the surface will be after mixing. Mixing may also be affected by the presence of physical obstructions which tend to block the supply of dilution water. Surface discharges entrain a flow at least equal to the discharge flow in the near field, often up to twenty times as much.

Beyond the near field mixing region of the discharge velocity and turbulence level are of the order of ambient values. In this "far field" region, further entrainment does not occur and the temperature distribution is determined by natural turbulent convection and diffusion. Ultimately all of the rejected heat contained in the discharge passes to the atmosphere through the water surface, a process driven by the elevated surface temperatures. These "far field" heat transfers are highly variable, being determined by local water currents, wind, and meteorological conditions.2/

2/Stolzenback, Adams, Harleman "A User's Manual for Three-Dimensional Heated Surface Discharge Computations", January 1973, Office of Research and Monitoring, U. S. Environmental Protection Agency, Washington, D.C. 20460

Final computer simulations of the discharge structure modifications assumed a reorientation of the discharge structures so that the condenser cooling water was discharged in a downstream direction at an angle of approximately 30° from teh near bank, and at a velocity of about 6' per second. These assumptions increased the momentum of the discharged water so that it would travel for a substantial distance downstream from the plant before being dissipated through entrainment and turbulence, hence aiding in eliminating the existing recirculation of heated water. In addition, the increased mixing of the plume with river water should rapidly decrease the temperature of the plume. The discharge angle of about 30° from the near bank is intended to establish a surface velocity having a downstream component across the entire river cross section below the location of the plant discharge and thus prevent recirculation of water to the plant intake during periods of low flow.

In the analysis of the discharge varying aspect ratios (the ratio of the height to the half width of the discharge) were evaluated in establishing the discharge configuration producing the most desirable plume characteristics. Configurations with relatively small aspect ratios produce a plume which is thin but spreads rapidly in comparison to higher aspect ratios which generate a deeper plume with more entrainment. Likewise, various Froude Numbers were evaluated to determine the effects of these variations on mixing zone size as well as depth of the plume.

It was concluded that for the Gaston application under a 14°F temperature rise condition, an aspect ratio of 2 and a Froude Number of 6.4 should result in a sufficiently bouyant and stable plume with characteristics suitable for the hydrology of the Coosa River in the vicinity of the plant. Assuming the worse case of a 21°F condenser rise, this aspect ratio yields a Froude Number of 5.

In order to accomplish these recommendations, the discharge from Units 1 and 2 would need to be seven feet wide and fourteen feet deep at the point of discharge to the river. The discharge from Units 3 and 4, because of their higher flow rate, would need to be about seven and one half feet wide and fifteen feet deep at the point of discharge to the river. This results in a velocity from Units 1 and 2 at the point of discharge of 6.2 feet per second and a velocity from Units 3 and 4 of 6 feet per second.

Figure 6 shows a plan view of the decay of surface temperatures predicted by the model assuming an intake temperature of 89°F and a rise of 13.7°F. Figure 7 shows the same for a condenser rise of 21.4°F. These two cases bracket the range of rises experienced under normal operating conditions. Table 1 gives the surface areas contained in the isotherms illustrated. This simulation assumes the two structures to exit from a single point. This assumption was made to more accurately reflect the hydraulic interaction of the two jets due to their orientation and close proximity to each other.

The maximum plume depth for this configuration is estimated to be about 27 feet. The maximum depth in the river near the plant, in the proximity of this plume, is in excess of 50 feet. Figure 8 shows the predicted depth profile of the plumes for the 13.7°F and 21.4°F rise cases, as well as the coincident maximum and average depths of the river moving downstream from the plant.

Additional bottom soundings made during the detailed structural design stage indicated a slightly shallower than expected bottom in front of the discharge structures. To minimize the potential for plume/bottom interference, the discharge configurations were changed to 7.5 feet wide by 12 feet deep. Results of resimulation of these configurations indicated no significant difference in plume behavior.

Although the model used in this analysis does not allow for bank interference, it was felt that results of this analysis could still be used to safely conclude that the recommended discharge configuration would produce a plume with sufficient momentum to carry several thousand feet downstream, while maintaining its buoyant stability. The effect of the banks should be to push the far field isotherms further down the river than predicted by the model.

## DISCHARGE STRUCTURE CONSTRUCTION

Several alternative designs and construction methods were evaluated as means of implementing the conceptual design. Because of the plant's importance meeting the electrical load on the interconnected Southern Company System, it was imperative that the modifications be accomplished with a minimum of unit outage. Preliminary design considerations utilizing cofferdams to dewater the open channel sections and provide room for construction estimated that the units would have to be off the line for several weeks. This method was eliminated because of the long outage and relatively high construction costs.

Engineering designs were made for two other methods; one consisting of a prefabricated steel structure and the other a sheet pile and concrete structure. The prefabricated steel concept was a floating structure which could be positioned in the open channel sections and sunk in place. The only unit outage would be the time needed to position and sink the structure and to make the necessary connections to the open channel section.

The method selected was one which used sheet pile wall cofferdams to dewater only the necessary construction area and to serve as retaining walls for the pouring of the concrete flume structures. Design drawings for this method are shown in Figures 9 and 10.

Unit outage for the construction work was prevented by coordinating the placing of the sheet pile walls with previously scheduled outage for precipitator modifications. The sheet piling left a portion of the open channels open so that the units could operate. During the time prior to the actual pouring of the concrete, only one circulating pump was operated to reduce the dynamic force of the discharge water on the cofferdams. After the concrete was poured (Figure 10) and allowed to set for 72 hours, the inlet and outlet walls were removed and sheet pile closure was made to route all flow through the flumes.

A final cost summary for these modifications follows:

| | |
|---|---|
| Detailed Engineering | $ 27,500 |
| Total Construction | 270,952 |
| Engineering & Overhead | 62,675 |
| Total Cost | $361,127 |

## ANALYSIS OF THERMAL SAMPLING TESTS

As previously described, these modifications were primarily intended to eliminate recirculation and reduce river temperatures in the warmer low-flow months. However, due to relatively low rainfall and reduced river flows, it was possible to conduct a thermal sampling test on December 19, 1976, after completion of the modifications, with a still river. Other tests have been made under varying river flow conditions.

Figures 11 thru 13 are cross sections of the river plotted from data taken on December 12, 1974, before the discharge structure modifications. The ambient temperature of the water on this day, as measured 4.3 miles upstream of the discharge structure, was 9.1° and the discharge temperature was 16.5°C. There was an average of about 7,000 cfs of flow in the river at Plant Gaston. Figure 11 shows a plume extending about 0.4 miles upstream from the discharge with surface temperatures greater than 13°C. Figure 12, at the discharge, shows the entire section of the river with heated water greater than 12°C in the first five foot layer. Figure 13 shows a 2.1°C rise at 5' depth one mile downstream.

Figures 14 thru 22 are plots of data taken on December 19, 1976, after the modifications. On this day, there was no flow in the river and the ambient temperature was 7.6°C. Figure 14 is a Planar plot of temperatures at the 5' depth. There is now a steep thermal gradient across the river at the discharge as a result of the rapid entrainment mixing and attendant cooling. Data indicates some warm water is moving back upstream on the far bank but it is doing so only after traveling downstream where it is cooling and entraining ambient water.

Figures 15, 16, and 17, cross sections upstream of the discharge, show much lower temperatures compared to Figures 11 and 12, even for a day with no river flow. Figures 18-22 show successive cross sections from the discharge (Figure 8) to 1290 yards downstream (Figure 12). These sections are evidence that the warmest portions of the plume do not leave the discharge side of the river. By the time the plume has extended across the river, there is only a 3.4°C maximum rise above ambient. The isotherms show the presence of good vertical stratification.

Figure 23 is a plot of three longitudinal thermal profiles of measurements made on December 10, 1976, where there was flow in the river. Again the effectiveness of the modification on reducing temperatures on the opposite bank can be seen. More importantly, at 1500 yards, there is only a 1°C rise over ambient.

Figures 24-35 are plots of a thermal sampling done on February 16, 1977. In this particular study, the persons taking the temperature readings took measurements within the limits of the plume boundary. There was a flow in the river of 5800 cfs and ambient was 6°C as measured upstream over a mile. Figures 24, 25, and 26 are plan views of isotherm plots at 0, 3, and 10 ft. depths, respectively. On this day, there was a shart division between the discharge plume and the rest of the river. There was little wind and the water was calm. A dye test conducted showed no dye crossing the center of the river or moving upstream. An apparent boundary was visible west of the center of the river which showed as a strip of extremely still water, one to two feet wide in a continuous line down from the area of the discharges. The sequential cross section plots (Figures 27 thru 35) illustrate how closely the thermal plume stays to the west bank. Figure 36 compares the predicted performance of the modifications with that measured on this day. When one takes into account the variation in river depth (as shown by the dashed line) there is good agreement between actual and predicted thermal plume depth moving down river along the plume centerline.

The sampling done on December 10, 1974, can be directly compared with that taken February 16, 1977, because conditions on these days are similar. Both days have low ambient temperatures and moderate river flows. Figure 37 is a graph of the increase and decrease in temperature rise above ambient from the intake thru 1500 yards downstream. The graph uses the difference between the highest temperature in the river at a cross section and the ambient temperature as measured upstream outside of the plume. This difference in temperature has been divided by the maximum temperature rise (as measured in the discharge) to unitize the answer for comparison. The divergence of the two plots upstream of the discharge indicates a large reduction in recirculation. Past 1500 yards, the residual temperature rise is lower in the sample taken after the modification.

## STATUS AND FUTURE WORK

With the completion of the previously described modifications in December, 1976, only a limited field testing program has been accomplished at this writing. In particular, testing of plume behavior and temperature under conditions of maximum natural river temperatures must await summer of 1977. However, visual observation and data taken in field studies to date indicate that the modified discharge structures do impart enough momentum to the plume to entrain surrounding water and carry it a sufficient distance downstream, while maintaining bouyancy and vertical thermal stratification.

In addition to the extensive thermal plume studies planned for the summer of 1977, a study of operating plant efficiency will be performed to measure the increase in generation performance resulting from reduced turbine back pressure.

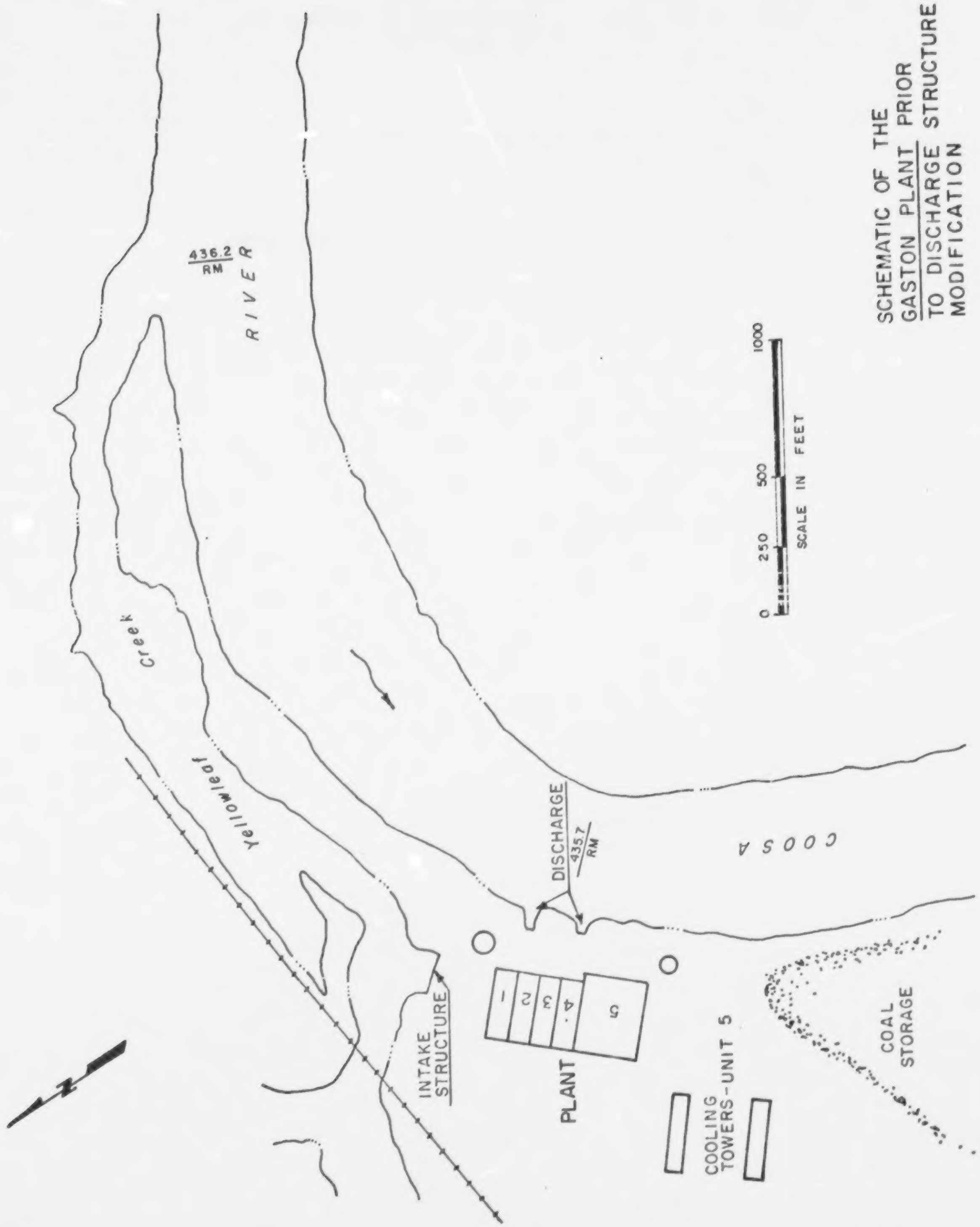
1/"Water Resources Data for Alabama, Part 2, Water Quality Records" United States Department of the Interior Geological Survey.

2/Stolzenback, Adams, Harleman "A User's Manual for Three-Dimensional Heated Surface Discharge Computations", January 1973, Office of Research and Monitoring, U. S. Environmental Protection Agency, Washington, D. C. 20460

## TABLE 1. SURFACE AREAS CONTAINED IN THEORETICAL PLUME ISOTHERMS

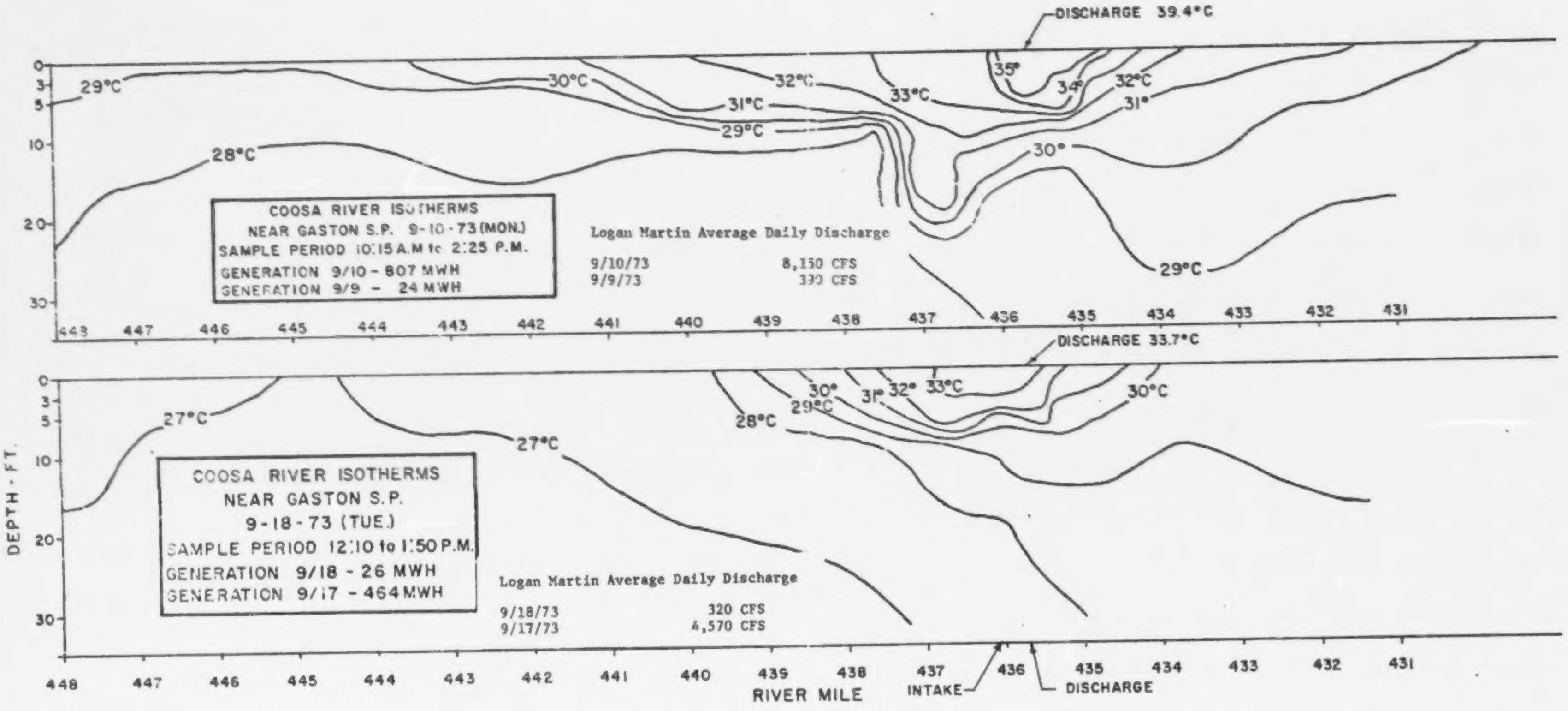
Intake Temperature = 89°F

| Isotherm Temperature | Condenser Rise 13.7°F | 21.4°F |
|---|---|---|
| 101 | | .11 acres |
| 98 | .04 acres | .18 |
| 96 | .11 | .55 |
| 95 | | .88 |
| 94 | .22 | 2.02 |
| 93 | .55 | 5.0 |
| 92 | 1.8 | 5.0 |


436.2
RM
RIVER
Creek
Yellowleaf
DISCHARGE
435.7
RM
COOSA
INTAKE
STRUCTURE
1
2
3
4
5
PLANT
COOLING
TOWERS-UNIT 5
COAL
STORAGE
0
250
500
1000
SCALE IN FEET
N

SCHEMATIC OF THE GASTON PLANT PRIOR TO DISCHARGE STRUCTURE MODIFICATION

FIGURE 1



COOSA RIVER ISOTHERMS NEAR PLANT GASTON
DURING SEPTEMBER 1973

FIGURE 2

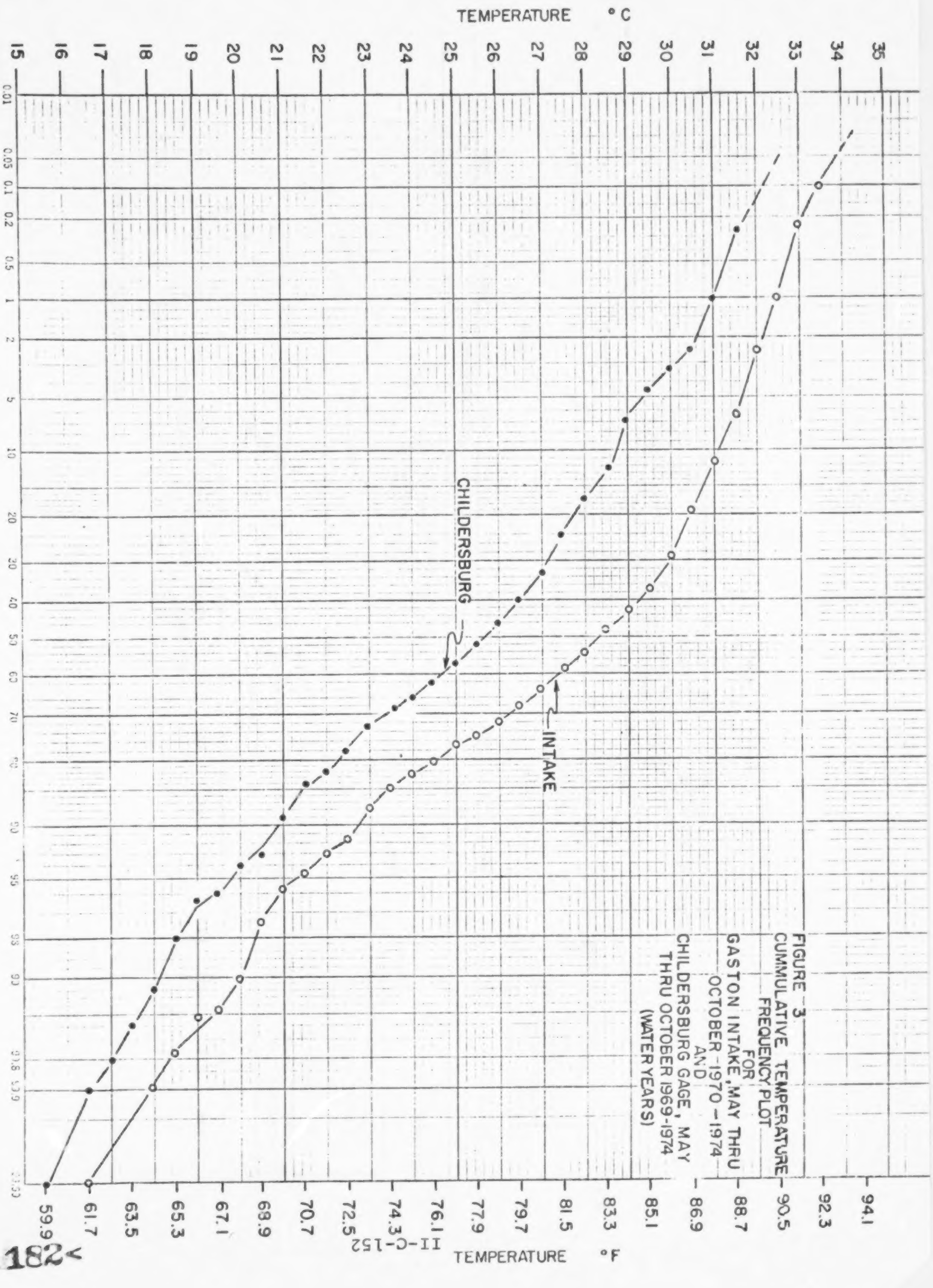
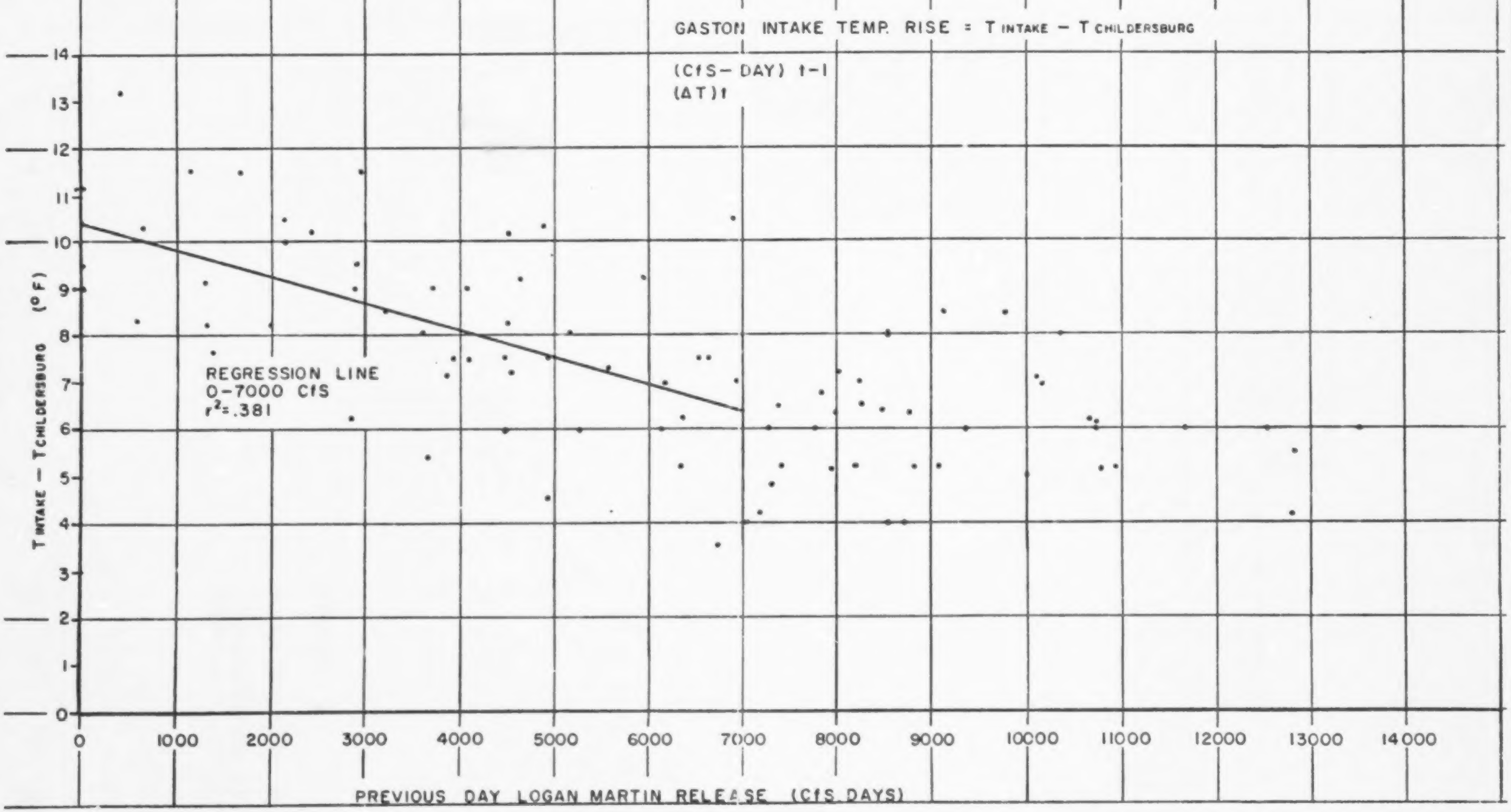
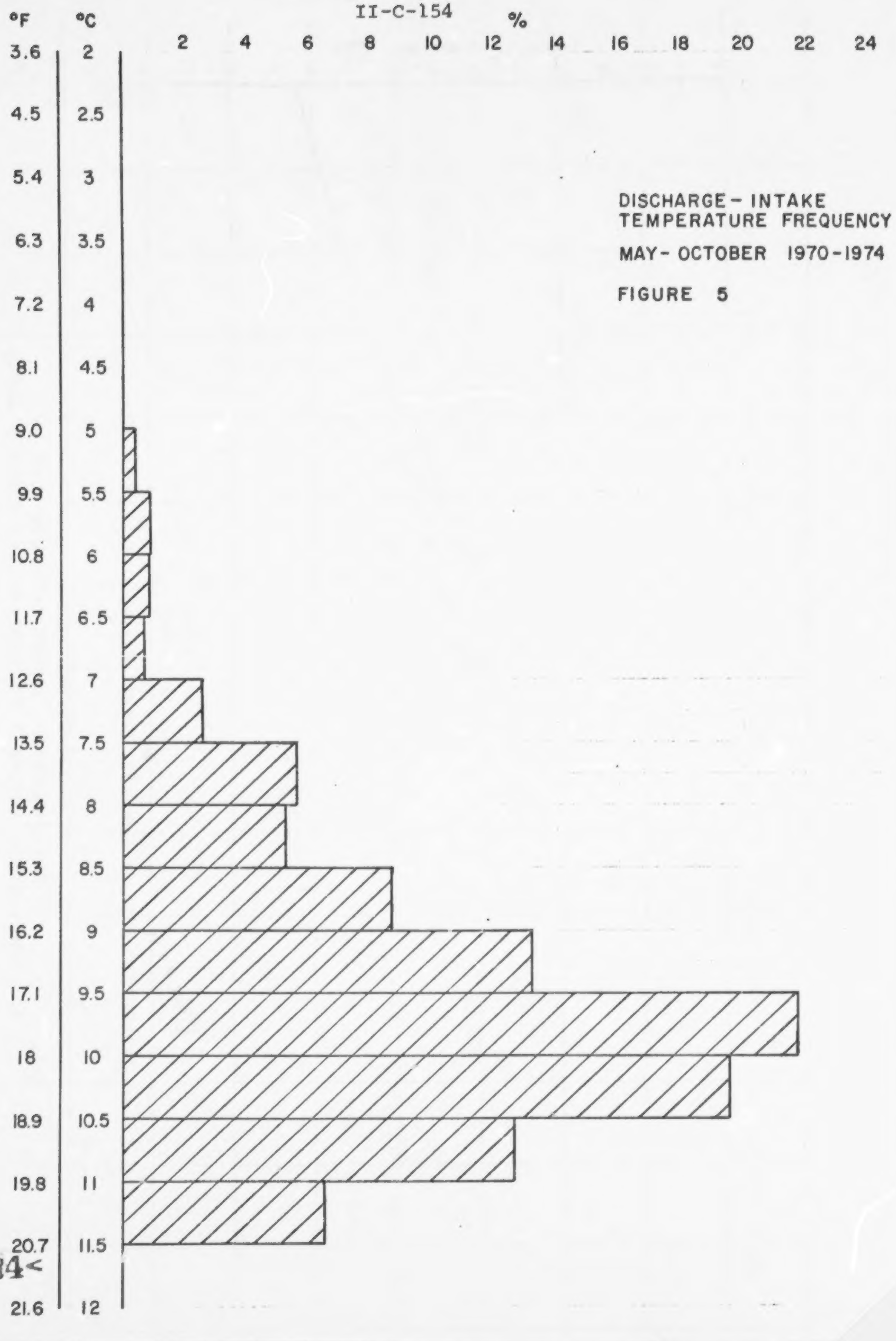


FIGURE 3
CUMMULATIVE TEMPERATURE
FREQUENCY PLOT
FOR
GASTON INTAKE, MAY THRU
OCTOBER 1970 – 1974
AND
CHILDERSBURG GAGE, MAY
THRU OCTOBER 1969-1974
(WATER YEARS)

FIGURE 4 LOGAN MARTIN RELEASES v GASTON INTAKE TEMP. RISE
DATA FOR JULY, AUGUST, SEPTEMBER 1972





DISCHARGE - INTAKE
TEMPERATURE FREQUENCY

MAY - OCTOBER 1970-1974

FIGURE 5

FIGURE 6

Predicted Surface Isotherms for Proposed Discharge Modifications
Intake Temperature - 89°F (31.7°C)
Condenser Rise - 13.7°F (approx. 7.5°C)
Isotherms Plotted: 98,96,94,93,92°F
(36.7, 35.6, 34.4, 33.9, 33.3°C)
---- Indicates edge of Plume ( △T=0)

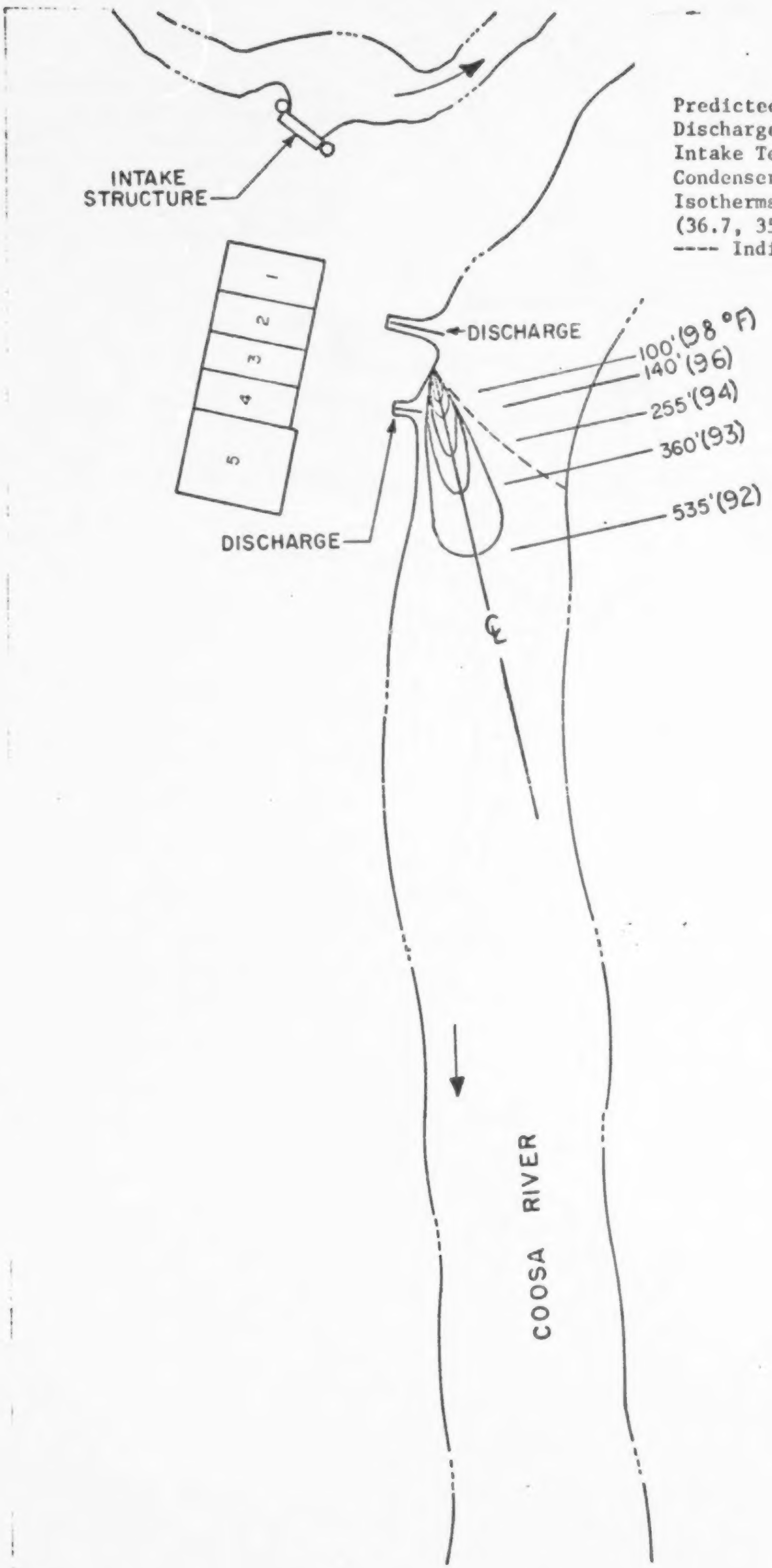
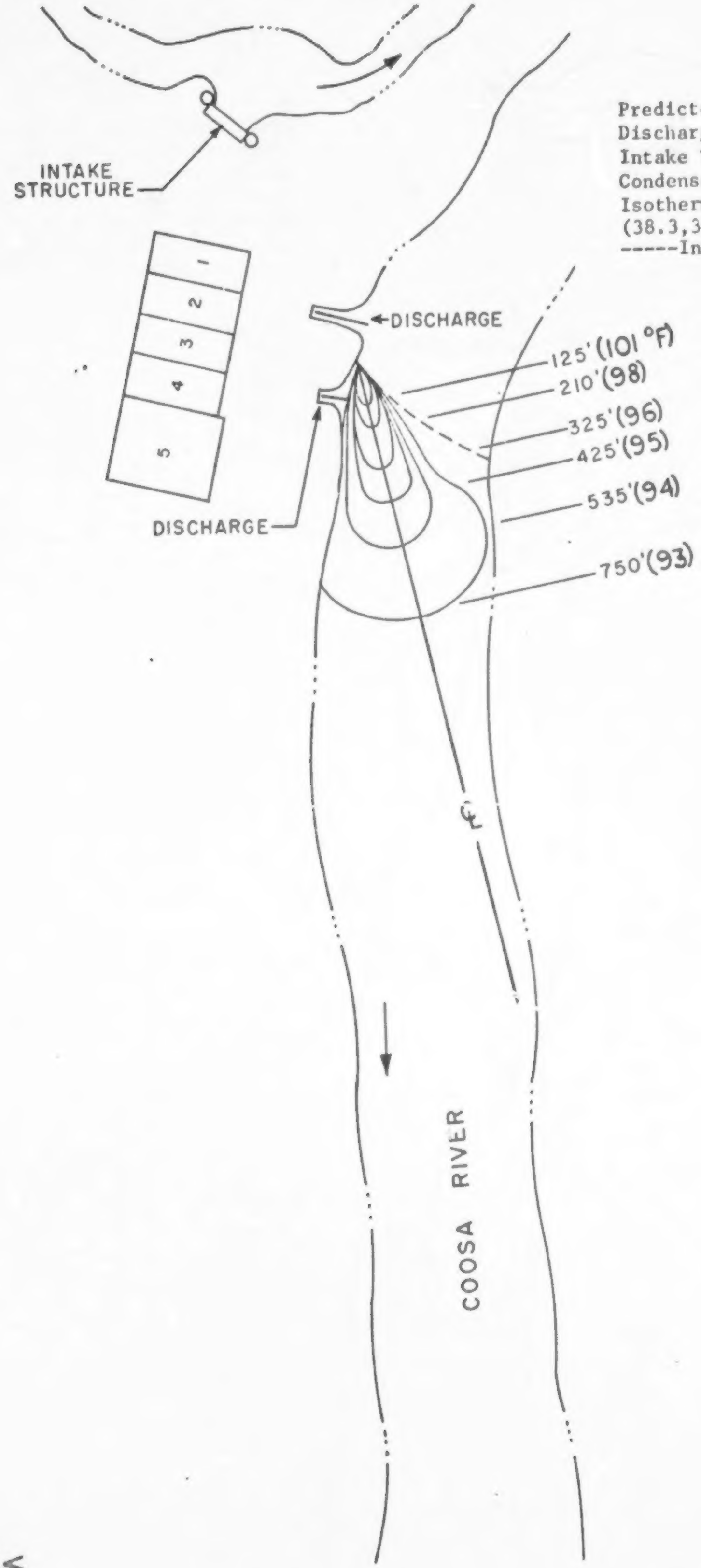

INTAKE STRUCTURE
1
2
3
4
5
DISCHARGE
DISCHARGE
100'(98 °F)
140'(96)
255'(94)
360'(93)
535'(92)
℄
COOSA RIVER

FIGURE 7

Predicted Surface Isotherms for Proposed Discharge Modifications
Intake Temperature - 89°F (31.7°C)
Condenser Rise - 21.4°F (approx. 12°C)
Isotherms Plotted: 101,98,96,95,94,93°F
(38.3,36.7,35.6,35.0,34.4,33.9°C)
-----Indicates edge of plume ( ΔT≅0)


INTAKE STRUCTURE
1
2
3
4
5
DISCHARGE
DISCHARGE
125'(101 °F)
210'(98)
325'(96)
425'(95)
535'(94)
750'(93)
℄
COOSA RIVER

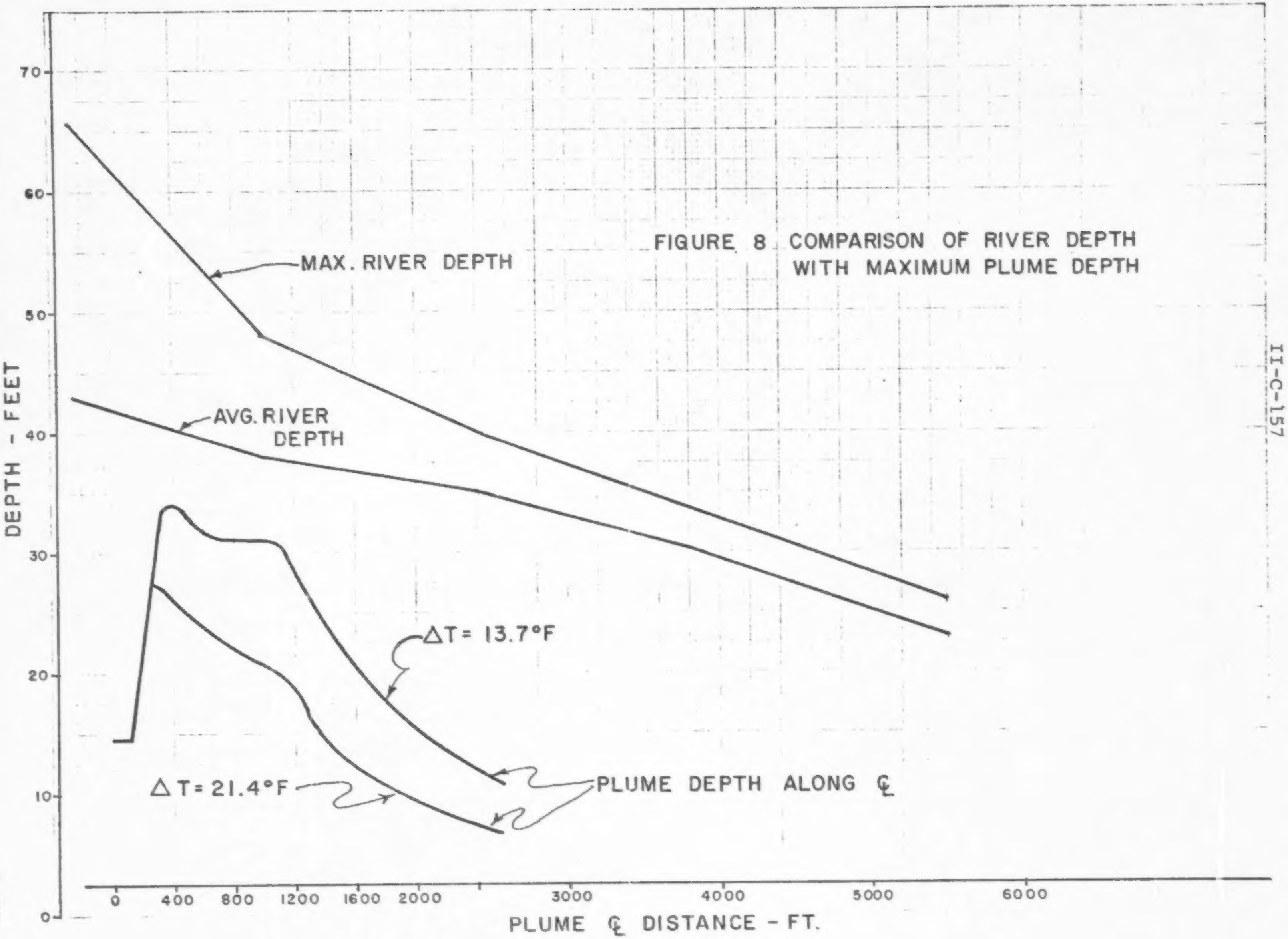


FIGURE 8 COMPARISON OF RIVER DEPTH WITH MAXIMUM PLUME DEPTH

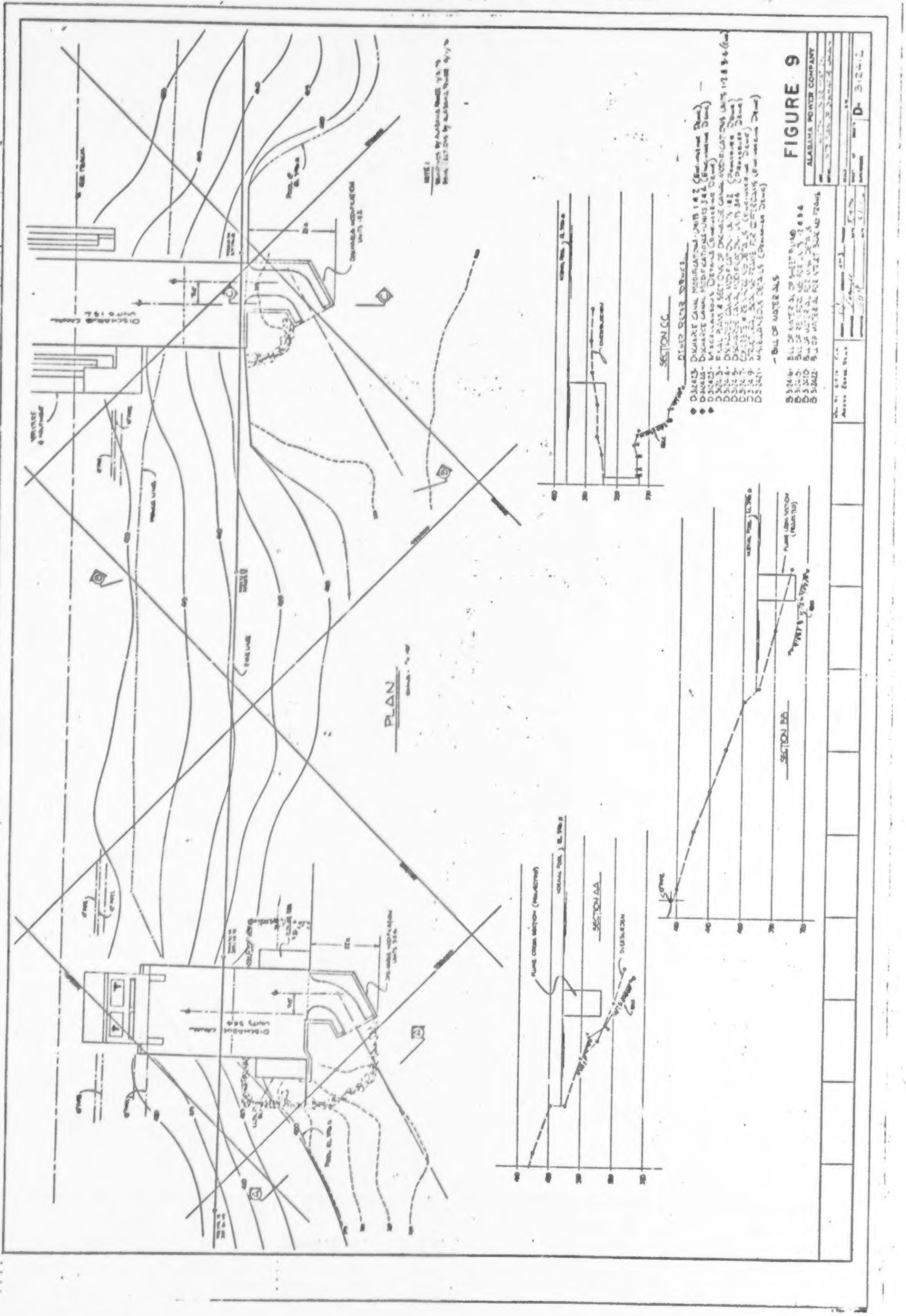


FIGURE 9
ALABAMA POWER COMPANY
PLAN
SECTION AA
SECTION BB
SECTION CC
DISCHARGE CANAL UNITS 1&2
DISCHARGE CANAL UNITS 3&4
OTHER REFER DRWGS.
BILL OF MATERIALS
D-

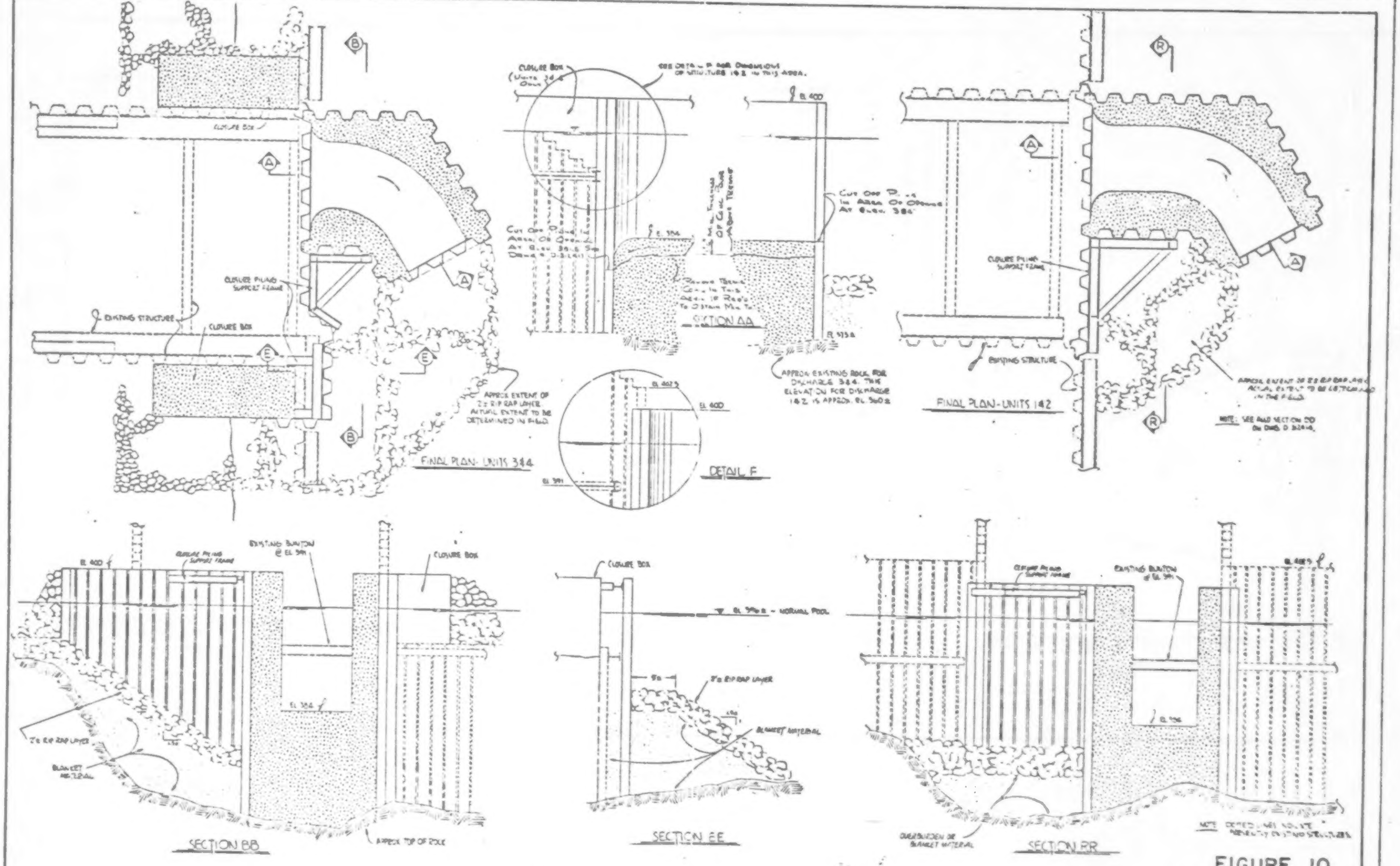

FINAL PLAN- UNITS 3&4
CLOSURE BOX
EXISTING STRUCTURE
CLOSURE PILING SUPPORT FRAME
APPROX EXTENT OF 2± RIP RAP LAYER ACTUAL EXTENT TO BE DETERMINED IN FIELD.
A
B
E
SECTION AA
CLOSURE BOX (UNITS 3&4 ONLY)
SEE DETAIL F FOR DIMENSIONS OF STRUCTURES 1&2 IN THIS AREA.
EL 400
EL 384
EL 373±
CUT OFF PILING IN AREA OF OPENING AT ELEV. 384
APPROX EXISTING ROCK FOR DISCHARGE 3&4. THIS ELEVATION FOR DISCHARGE 1&2 IS APPROX. EL 360±
DETAIL F
EL 402.5
EL 400
EL 391
FINAL PLAN-UNITS 1&2
NOTE: SEE AAA SECTION DD ON DWG. D 3244.
R
SECTION BB
EXISTING BUNTON @ EL 391
CLOSURE PILING SUPPORT FRAME
2± RIP RAP LAYER
BLANKET MATERIAL
APPROX TOP OF ROCK
SECTION EE
EL 394± - NORMAL POOL
2'± RIP RAP LAYER
BLANKET MATERIAL
SECTION RR
OVERBURDEN OR BLANKET MATERIAL
NOTE: DOTTED LINES INDICATE PRESENTLY EXISTING STRUCTURES

FIGURE 10

ALABAMA POWER COMPANY

D- 3243

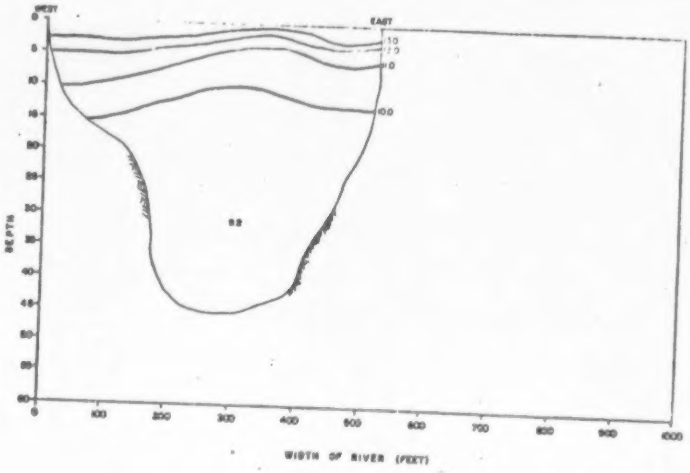


FIGURE 11
CROSS-SECTION AT R.M. 436.1
December 12, 1974

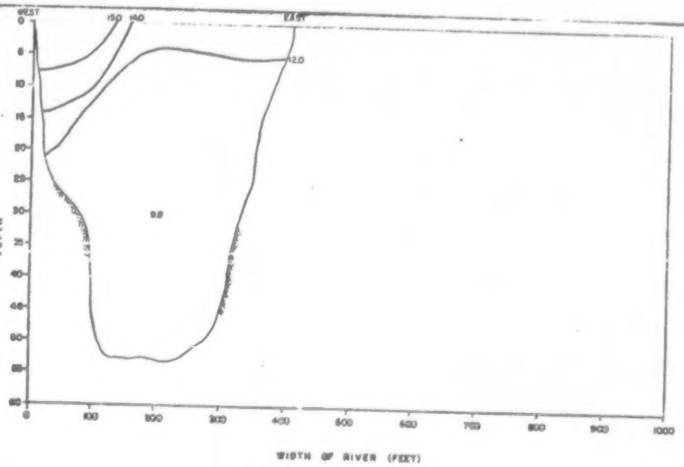


FIGURE 12
CROSS SECTION AT R.M. 435.7
(DISCHARGE)

December 12, 1974

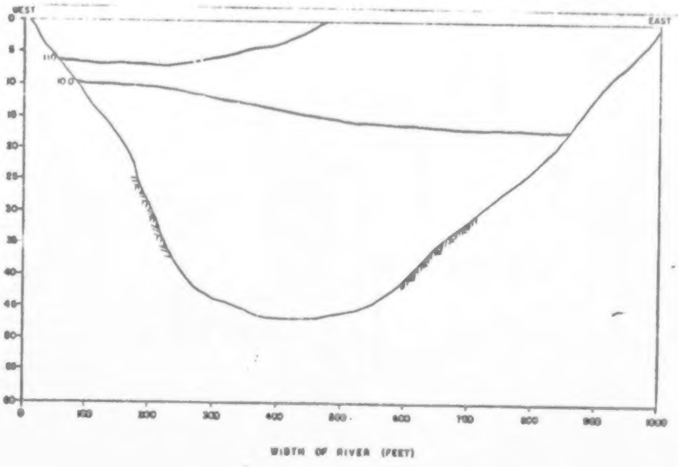


FIGURE 13
CROSS SECTION AT R.M. 434.8
December 12, 1974

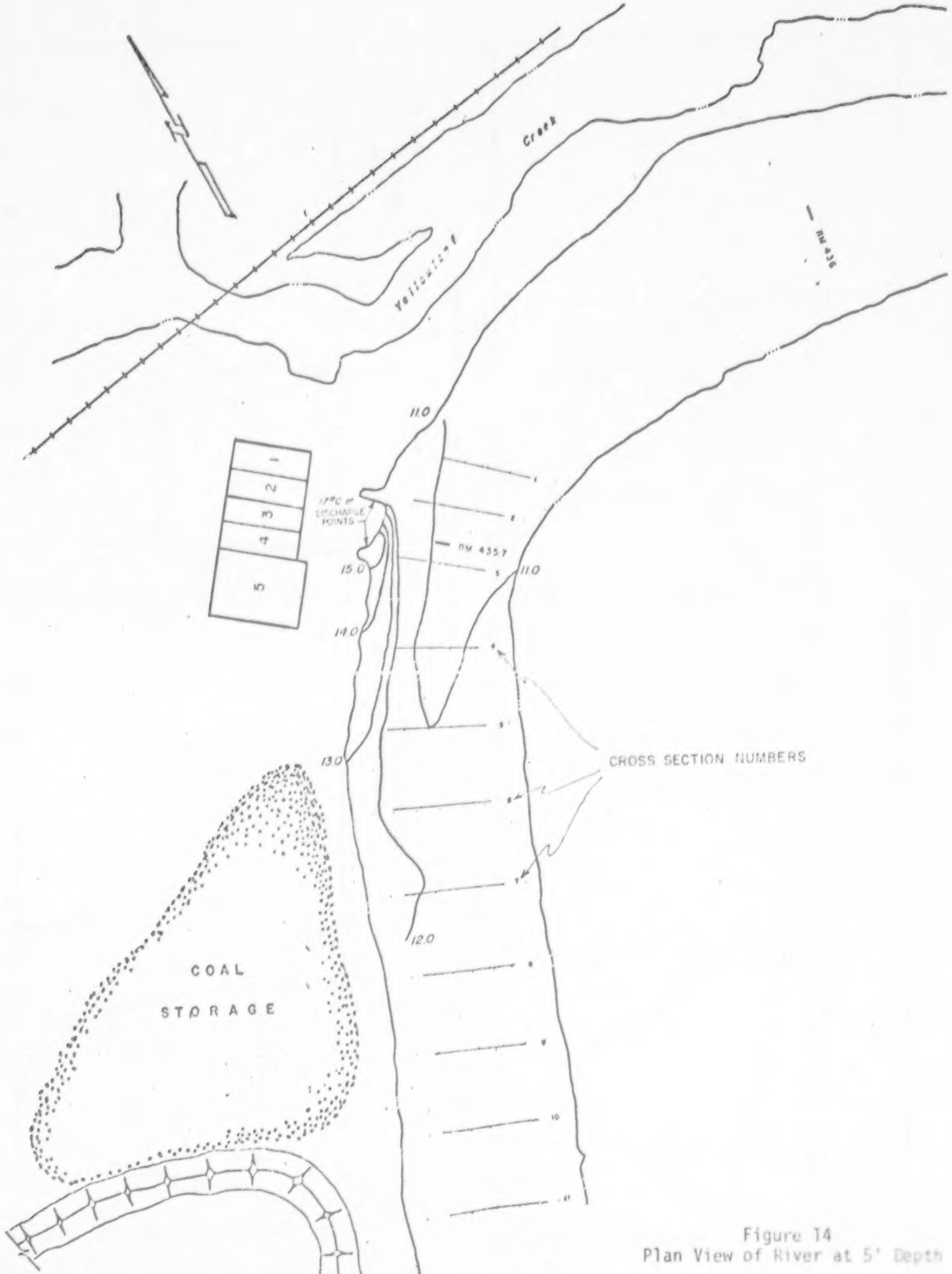

Creek
RM 436
11.0
1
2
3
4
5
17°C at DISCHARGE POINTS
RM 435.7
15.0
11.0
14.0
13.0
12.0
CROSS SECTION NUMBERS
COAL STORAGE

Figure 14
Plan View of River at 5' Depth

December 19, 1976

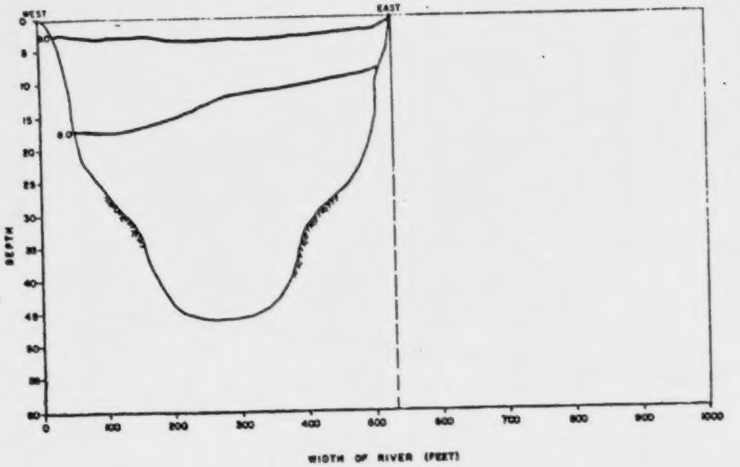


FIGURE 15

CROSS SECTION AT R.M. 436.5

December 19, 1976

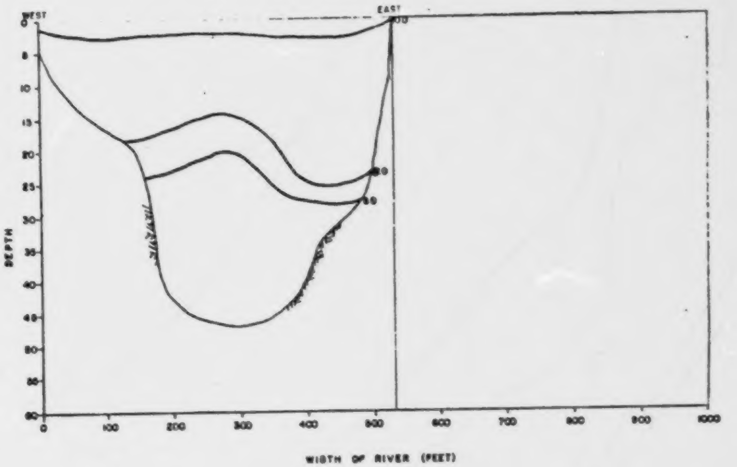


FIGURE 16

CROSS SECTION AT R.M. 436.1

December 19, 1976

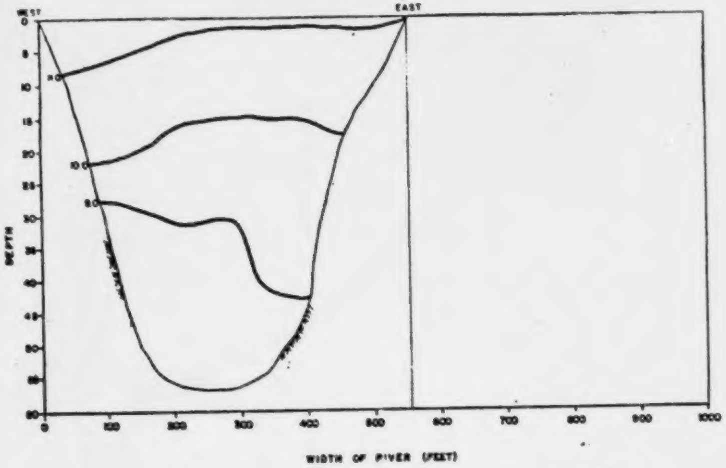


FIGURE 17
CROSS SECTION #1 (170 YARDS
UPSTREAM OF DISCHARGE)

December 19, 1976

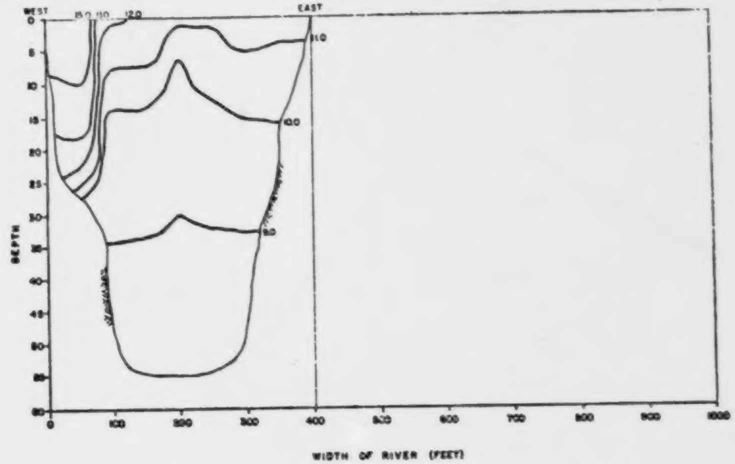


FIGURE 18
CROSS SECTION #3 (DISCHARGE)

December 19, 1976

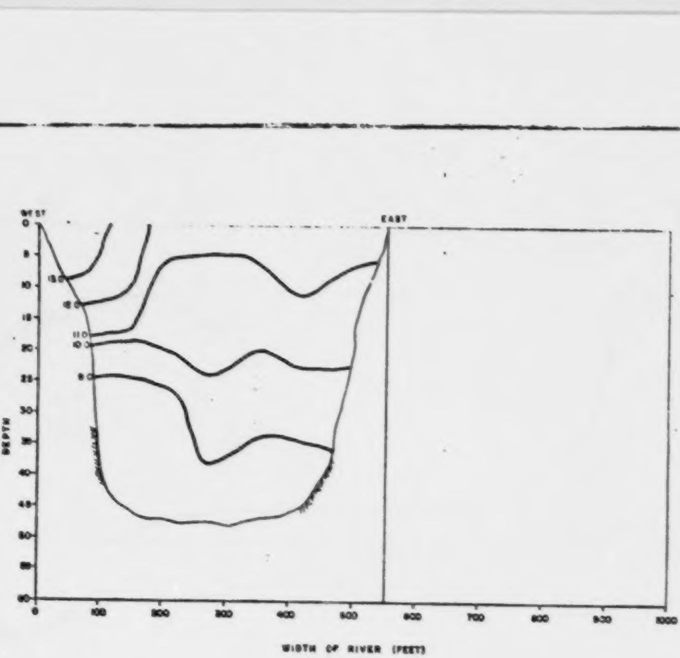


FIGURE 19
CROSS SECTION #5 (172 YARDS
DOWNSTREAM OF DISCHARGE)

December 19, 1976

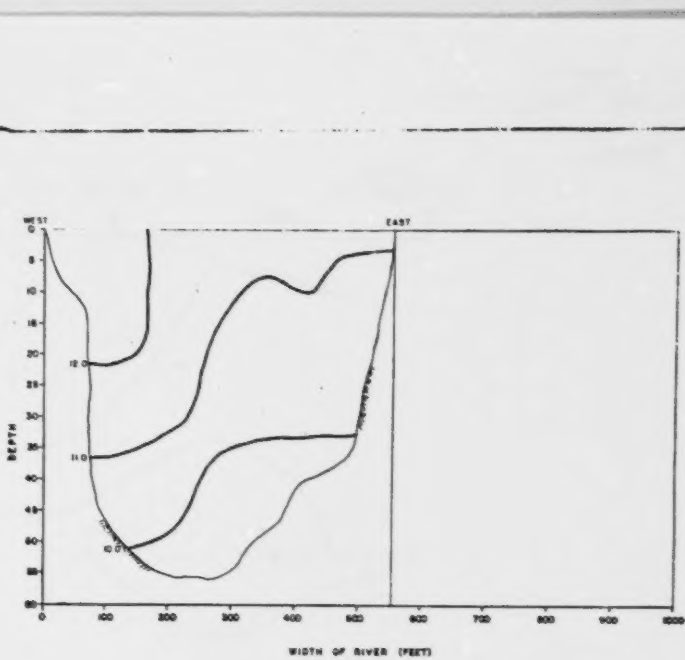


FIGURE 20
CROSS SECTION #7 (344 YARDS
DOWNSTREAM OF DISCHARGE)

December 19, 1976

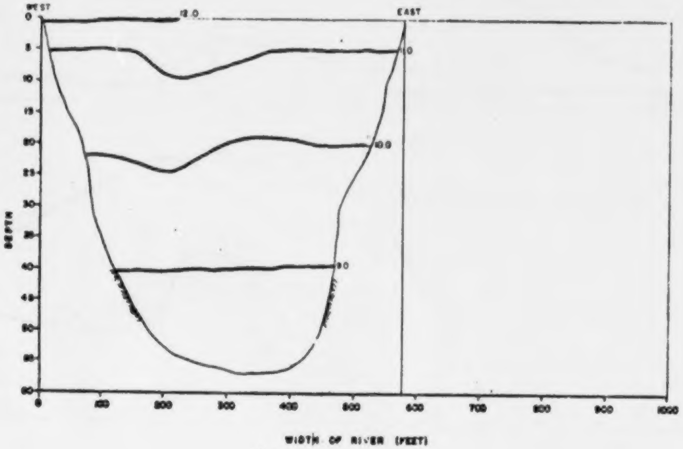


FIGURE 21
CROSS SECTION #12 (774 YARDS
DOWNSTREAM OF DISCHARGE)

December 19, 1976

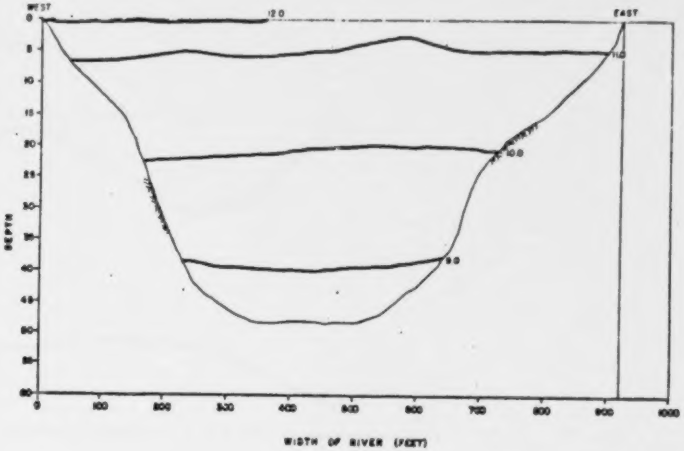


FIGURE 22
CROSS SECTION #18 (1250 YARDS
DOWNSTREAM OF DISCHARGE)

December 19, 1976

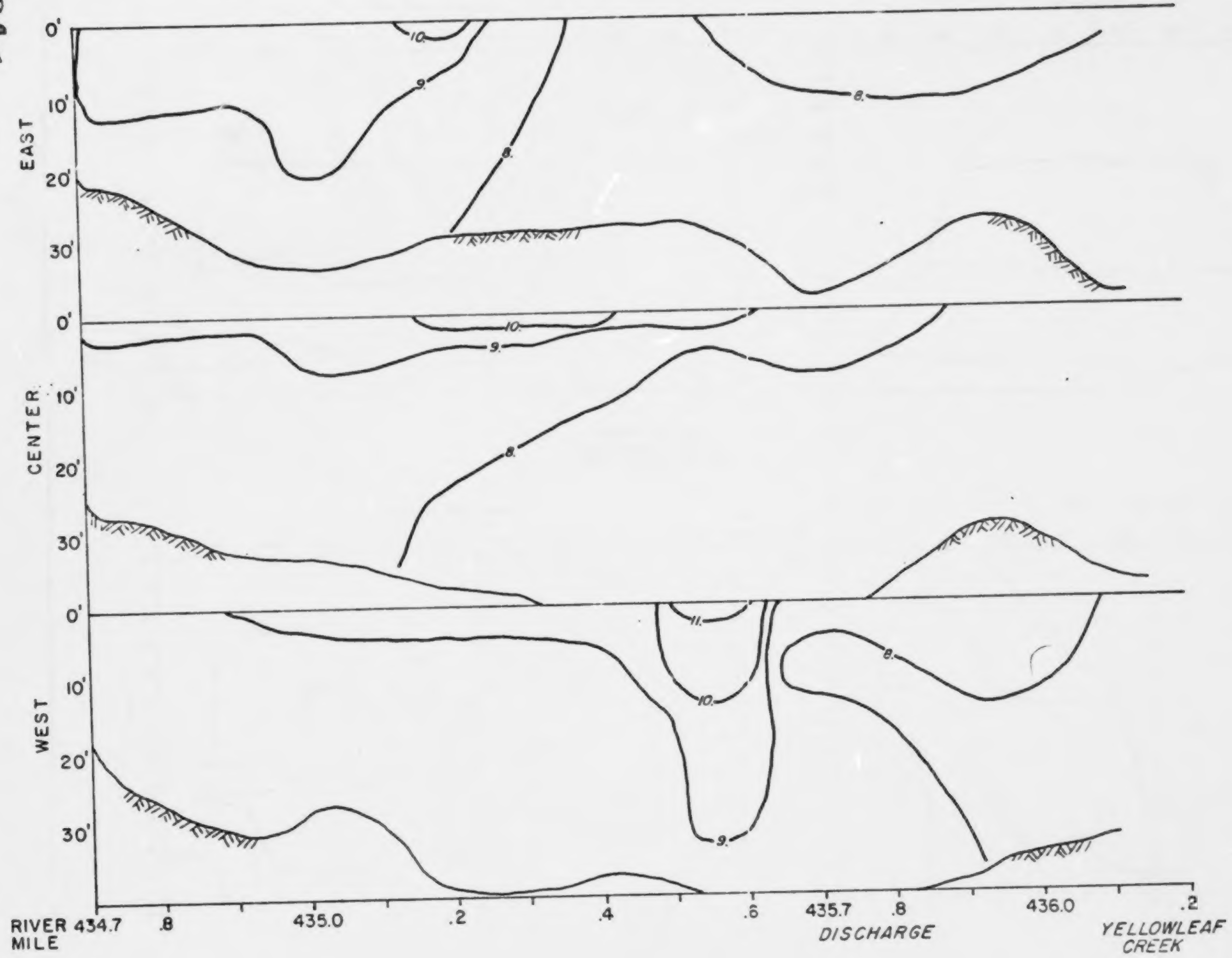


FIGURE 23

LONGITUDINAL PROFILES OF RIVER
December 10, 1976

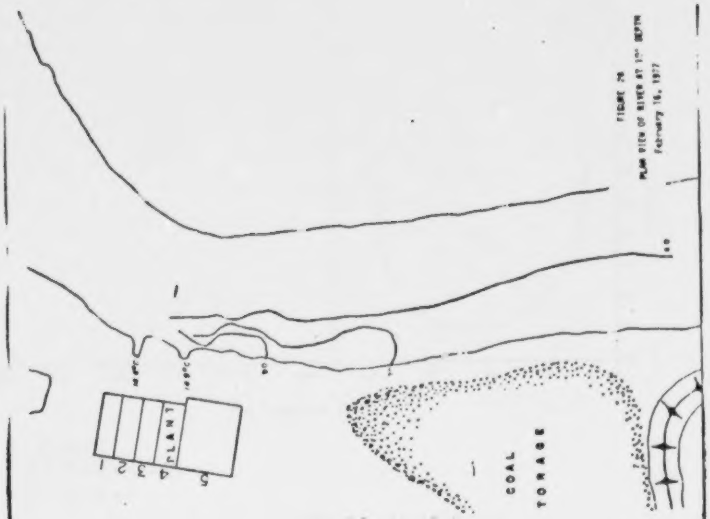

1
2
3
4
5
PLANT
COAL
TORAGE

FIGURE 26
PLAN VIEW OF RIVER AT 10' DEPTH
February 16, 1977

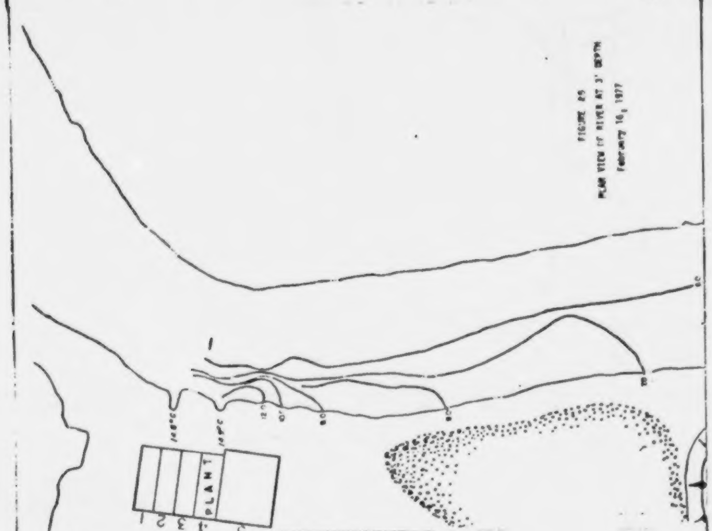

1
2
3
4
5
PLANT

FIGURE 25
PLAN VIEW OF RIVER AT 5' DEPTH
February 16, 1977

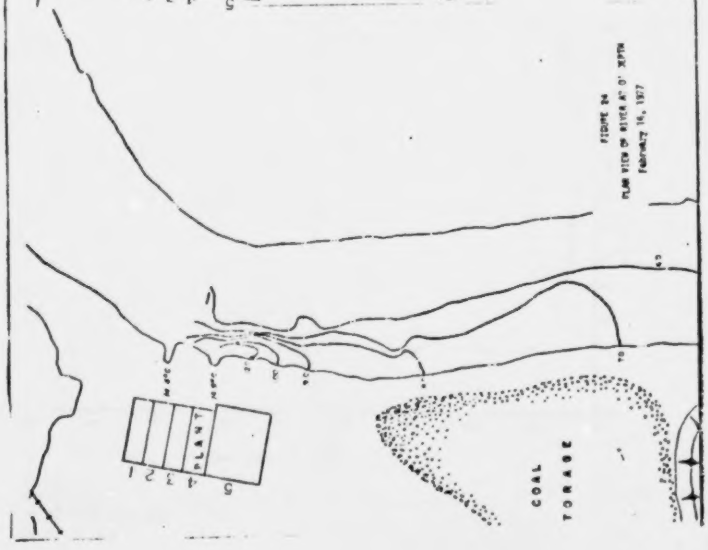

1
2
3
4
5
PLANT
COAL
TORAGE

FIGURE 24
PLAN VIEW OF RIVER AT 0' DEPTH
February 16, 1977

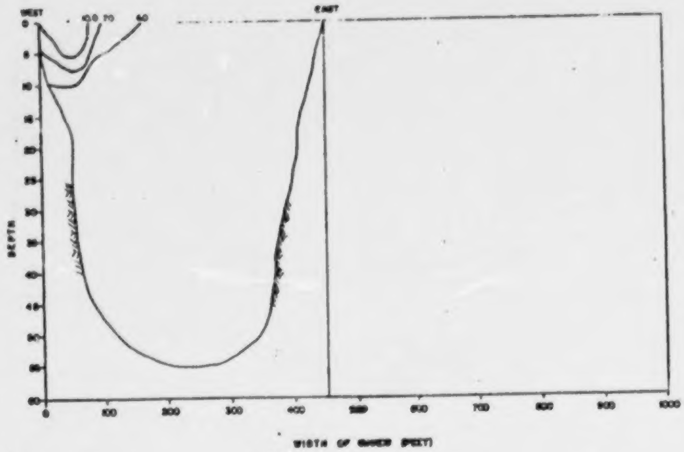


FIGURE 27
CROSS SECTION
([illegible] YARDS DOWNSTREAM OF DISCHARGE)

February 16, 1977

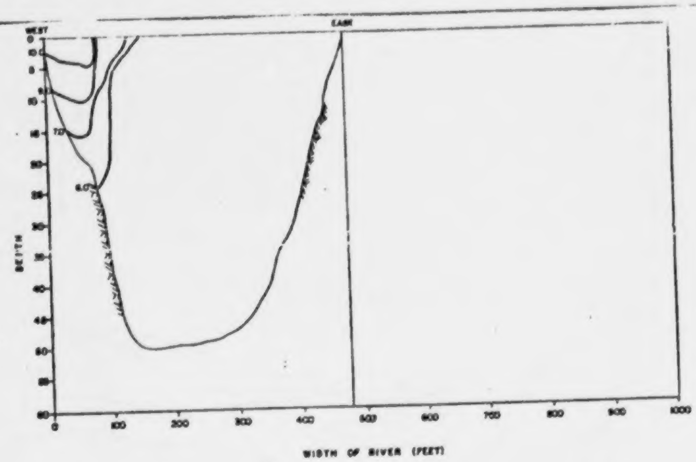


FIGURE 28
CROSS SECTION
(67 YARDS DOWNSTREAM OF DISCHARGE)

February 16, 1977

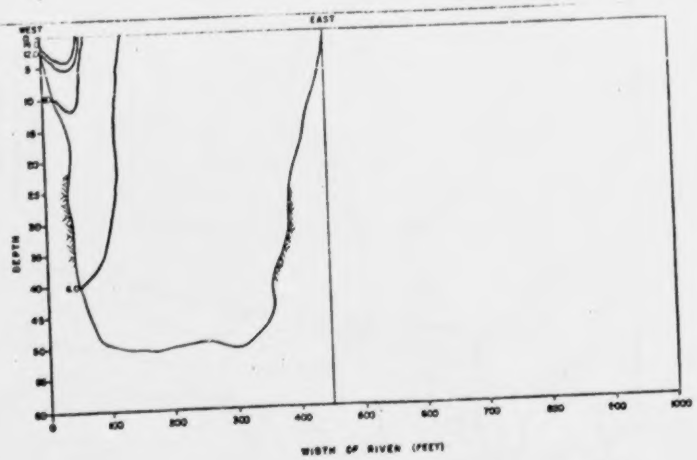


FIGURE 29
CROSS SECTION
(102 YARDS DOWNSTREAM OF DISCHARGE)

February 16, 1977

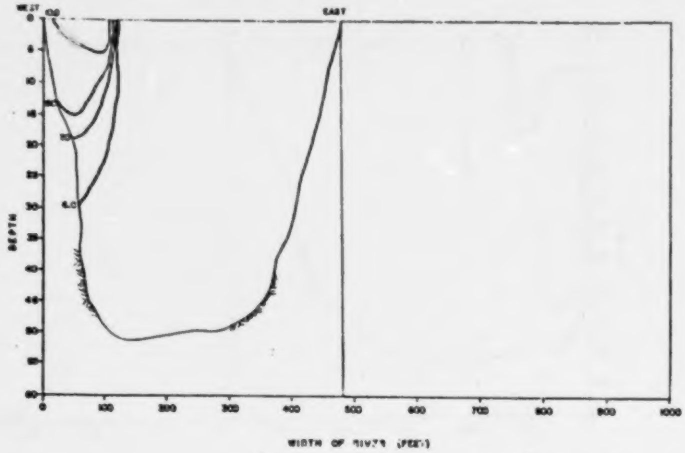


FIGURE 30
CROSS SECTION
(126 YARDS DOWNSTREAM OF DISCHARGE)

February 16, 1977

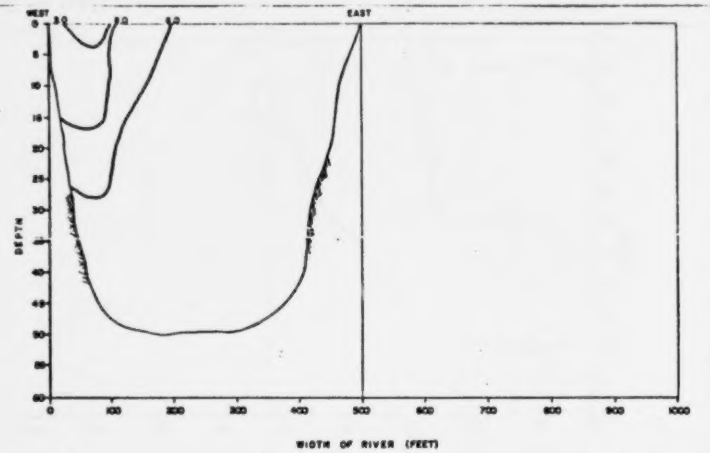


FIGURE 31
CROSS SECTION
(188 YARDS DOWNSTREAM OF DISCHARGE)

February 16, 1977

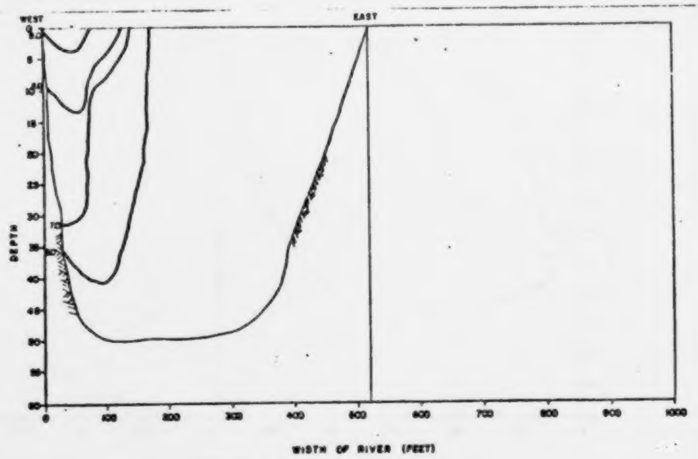


FIGURE 32
CROSS SECTION
(210 YARDS DOWNSTREAM OF DISCHARGE)

February 16, 1977

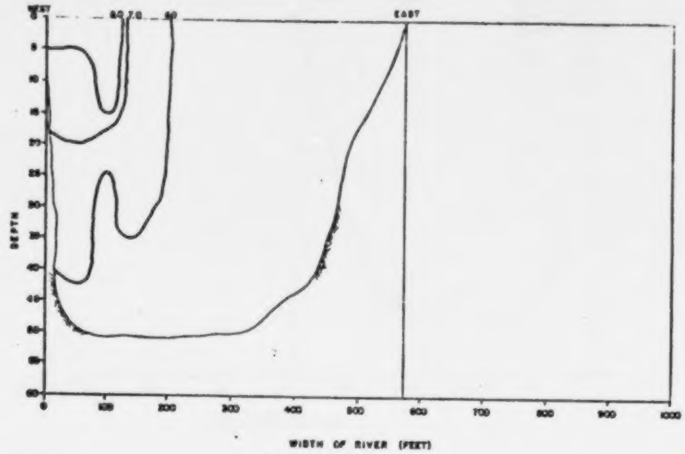


FIGURE 33
CROSS SECTION
(357 YARDS DOWNSTREAM OF DISCHARGE)

February 16, 1977

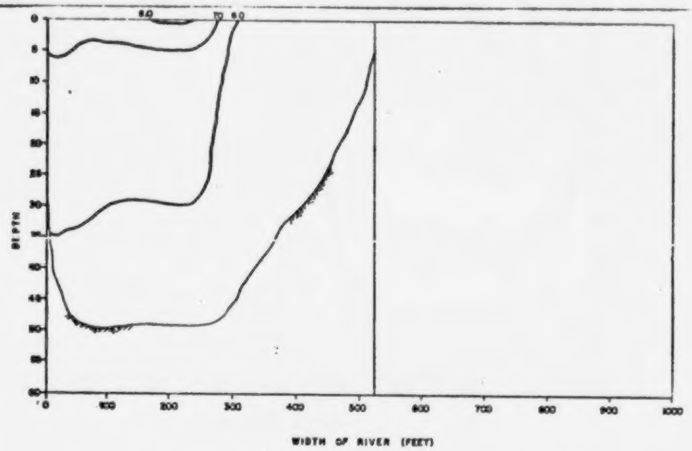


FIGURE 34
CROSS SECTION
(612 YARDS DOWNSTREAM OF DISCHARGE)
February 16, 1977

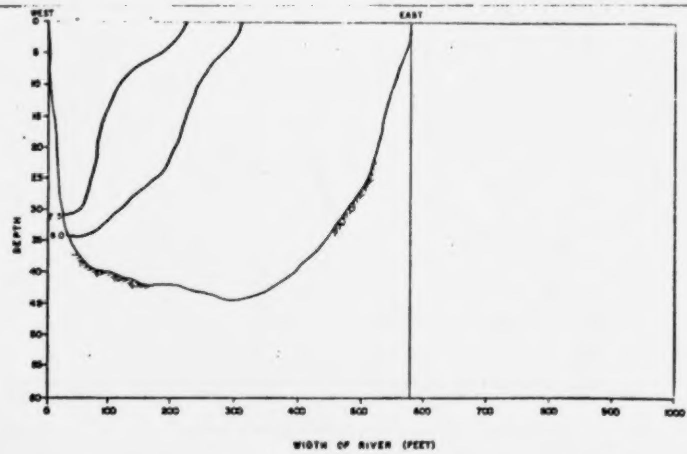


FIGURE 35
CROSS SECTION
(803 YARDS DOWNSTREAM OF DISCHARGE)

February 16, 1977

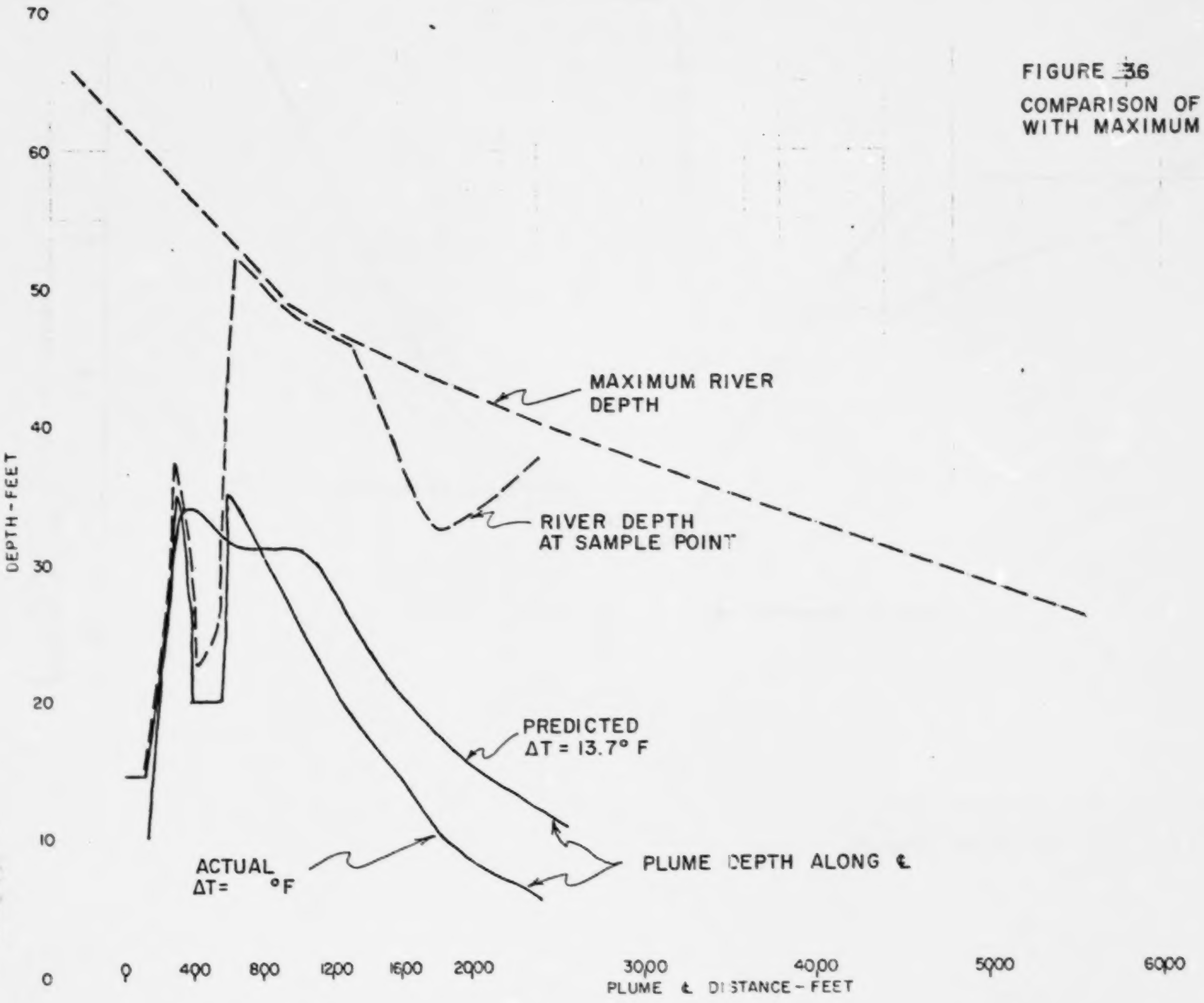


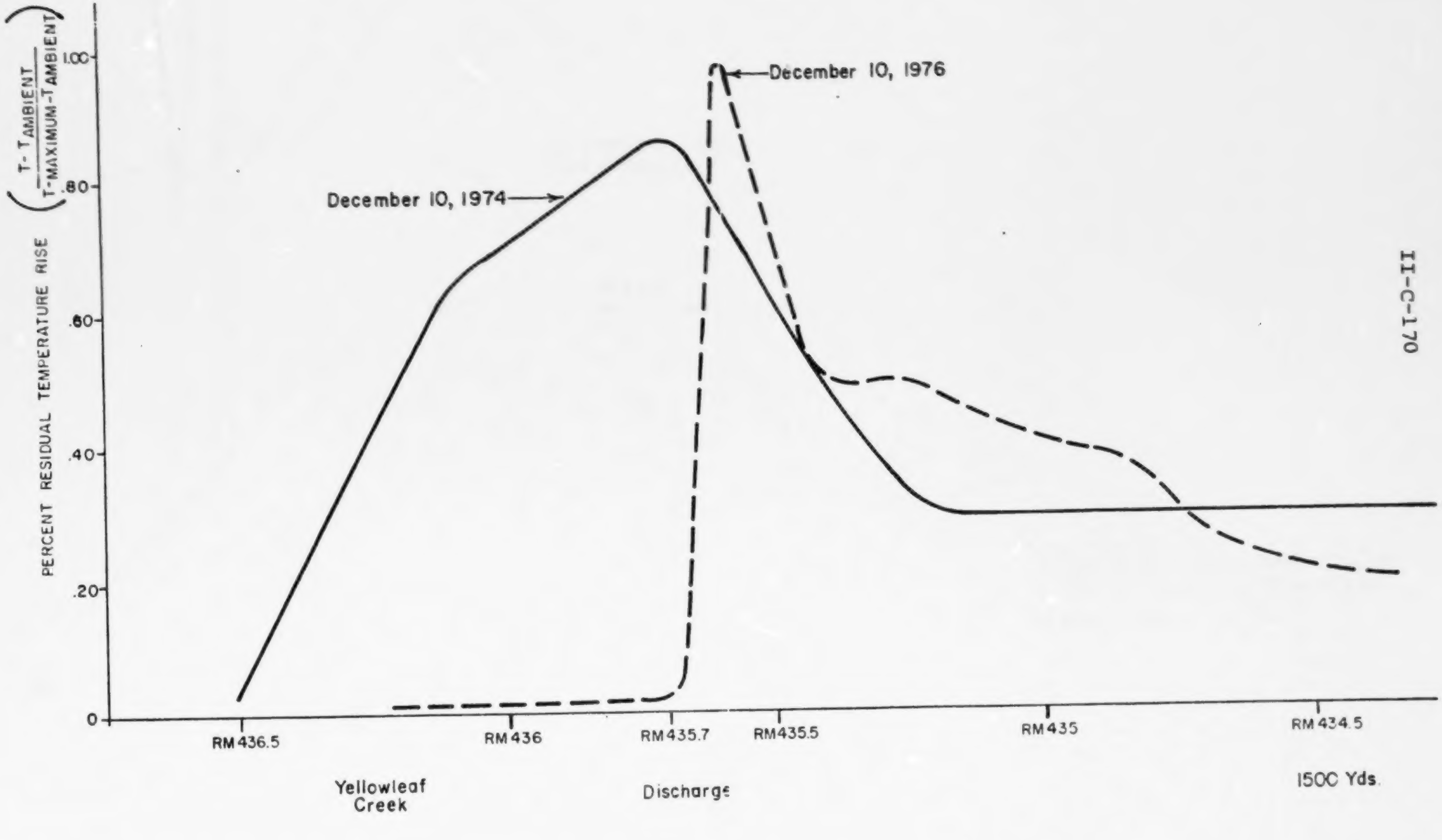
FIGURE 36

COMPARISON OF RIVER DEPTH WITH MAXIMUM PLUME DEPTH

32

200<

FIGURE 37
RESIDUAL TEMPERATURE RISE IN THE COOSA RIVER
IN THE VICINITY OF THE GASTON PLANT BEFORE AND
AFTER DISCHARGE STRUCTURE MODIFICATIONS



## Session 2C

## Dry Cooling for Power Plants: Incentives, Problems and Research/Development Activities

II-C-171

# COMPARISON OF ALTERNATIVE DIFFUSER DESIGNS FOR THE DISCHARGE OF HEATED WATER INTO SHALLOW RECEIVING WATER

E.E. Adams and K.D. Stolzenbach
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

## ABSTRACT

Submerged multi-port diffusers represent the most efficient means for rapidly dispersing large volumes of heated water from power plants into shallow waterbodies such as continental shelves, lakes or large rivers. An examination of existing diffuser designs reveals that the majority may be classified into one of four categories-- co-flowing, tee, staged and alternating-- characterized by the orientation of the diffuser nozzles, pipeline and local current. The first three employ horizontal momentum to induce an entrainment current and the preferred design for a given location depends on the predominant current speed and direction. The alternating diffuser does not induce any net momentum, and while a longer diffuser is generally required to achieve any level of mixing, several secondary advantages may accrue with this design. Formulas for the near field dilution under limiting conditions are presented for each diffuser type and an example design comparison shows the sensitivity of the diffusers' performance to various plant, cooling system and environmental variables.

## INTRODUCTION

In the past five to ten years a number of submerged, multi-port diffusers have been designed to discharge heated water from large steam electric generating stations which employ once-through cooling systems. The basic principle in these diffusers is that by discharging the flow through a number of individual ports, the total area available for jet entrainment is increased and hence rapid dilution of the discharged water can be obtained. This is especially important when considering large generating stations which have substantial cooling water flow rates, and when considering shallow receiving water bodies where the quantity of water available for dilution is limited. In this paper, the near field mixing characteristics of several basic types of shallow water diffusers are summarized and the example calculations are used to compare their performance under a range of conditions.

The variables used to describe a multi-port diffuser are shown in the definition sketch of Figure 1. In this paper, diffuser performance will be based on a characteristic maximum surface temperature induced in the near field. To eliminate consideration of local hot spots caused by single jets, $T_{max}$ will be loosely defined as the highest surface temperature for which a closed isotherm greater than a certain minimum size can be drawn. It must be noted that this is just one of many criteria which can be used to evaluate diffuser designs. Defining the near field dilution S in terms of $T_{max}$ one can write

$$S = \frac{T_o - T_a}{T_{max} - T_a} = \frac{\Delta T_o}{\Delta T_{max}} = \text{function}\left[\mathbb{F}_o\ \frac{V}{u_o},\ \frac{L}{H},\ \frac{\ell}{H},\ \frac{D_o}{H},\ \frac{h}{H},\ \alpha,\ \beta,\gamma\right] \quad (1)$$

where

$$\mathbb{F}_o = \frac{u_o}{\sqrt{\dfrac{\Delta\rho_o}{\rho_a}\, gD_o}}$$

and $\Delta\rho_o/\rho_a$ is the relative density difference associated with $\Delta T_o$ and $T_a$. For closely spaced ports, $\ell \leq H$, the influence of individual ports will not be felt, and for the purposes of analysis, the individual ports may be replaced by an equivalent slot diffuser having the same discharge and momentum flux per unit length [1], [2]. Thus the width $B_o$ of an equivalent slot diffuser is $\pi D_o^2/4\ell$. In addition, in shallow water, the port elevation is of secondary significance as long as $h/H \leq .5$. With these assumptions the dilution may now be written

$$S = \text{function}\left[\mathbb{F}_s,\ \frac{V}{u_o},\ \frac{L}{H},\ \frac{H}{B_o},\ \alpha,\ \beta,\ \gamma\right] \quad (2)$$

where

$$\mathbb{F}_s = \frac{u_o}{\sqrt{\dfrac{\Delta\rho_o}{\rho_a}\, gB_o}}$$

Whether or not the receiving water is shallow will depend on the type of diffuser under consideration but in general the condition will hold if H satisfies a relationship of the form

$$\frac{H}{B_o} < \text{function}\left[\mathbb{F}_s,\ \frac{V}{u_o},\frac{L}{H},\ \alpha,\ \beta,\ \gamma\right] \quad (3)$$

The above two functions have been evaluated for four basic types of diffusers distinguished by the values of the angles $\alpha$, $\beta$, and $\gamma$. These types have been loosely referred to as co-flowing, tee, staged and alternating diffusers. While clearly not an exhaustive list, these types represent the range of shallow water diffusers which have been designed to date.

## DISCUSSION OF INDIVIDUAL DESIGNS

The four types of diffusers, and typical flow fields which might be observed by the operation of the diffuser in a coastal area are shown in Figure 2. Salient features and near field dilution relationships for each design are discussed below and the relative advantages are summarized in Table 1. More discussion regarding the analyses can be found in the references noted or in reference [3].

### Co-Flowing Diffusers ($\alpha \sim 0^\circ$, $\beta \sim 0^\circ$, $\gamma \sim 90^\circ$)

In this type of diffuser, the nozzles are oriented essentially horizontally (a small angle $\alpha \approx 20^\circ$ may be desirable to prevent bottom scour) and at right angles to the diffuser line as indicated in Figure 2(a). Flow is induced primarily from behind the diffuser with additional mixing caused by lateral entrainment at the ends of the diffuser. In a co-flowing situation, dilution is augmented by the flow of ambient water which would pass naturally over the diffuser. For long diffuser, $L/H \gtrsim 10$, end effects can be neglected and the flow entering the diffuser is proportional to the dilution $S_c$. An analysis based on continuity, one-dimensional momentum equations and the Bernoulli equation evaluated along a streamline gives [4]

$$S_c = \frac{1}{2}\left[\frac{VH}{u_oB_o} + \sqrt{\left(\frac{VH}{u_oB_o}\right)^2 + \frac{2H\cos\alpha\sin\gamma}{B_o}}\right] \qquad (4)$$

In the limit of no current, the dilution is given by

$$S_c = \sqrt{\frac{H\cos\alpha\sin\gamma}{2B_o}} \qquad (5)$$

while for a strong ambient current the dilution approaches the ratio of the flow which would pass over a dormant diffuser to the diffuser discharge flow, or

$$S_c = \frac{VH}{u_oB_o} \qquad (6)$$

In Equation (4) it is noted that the parameter $\mathbb{F}_s$ does not appear. This is because, for shallow water, $\mathbb{F}_s$ is large and the influence of buoyancy for this diffuser type is relatively unimportant. A criterion for shallow water is that the heated flow away from the diffuser be attached to the bottom, or that the densimetric Froude number based on water depth and on the mixed flow velocity and density difference by greater than unity. For these conditions the criterion for shallow water is

$$\frac{H}{B} < \frac{1}{2}\,\mathbb{F}_s^{4/3} \qquad (7)$$

2[illegible]4<

In order that the temperature downstream be truly uniform over depth, a somewhat stricter relationship must hold.

A comparison of predicted dilutions with those observed in experimental model studies, for cases in which L/H > 10 and Equation (7) is satisfied, is presented in Figure 3. A comprehensive study of co-flowing diffusers including end effects, is in progress [5].

If the current opposes the diffuser nozzles ($\gamma \sim -90^o$), Equation (4) may be used as long as

$$\frac{VH}{u_o B_o} > \left| \frac{2H\cos\alpha \sin\gamma}{B_o} \right| \tag{8}$$

If this inequality is not satisfied, direct re-entrainment of the plume will occur as depicted in Figure 2(b), and the effective dilution will decrease sharply causing $T_{max}$ to rise. Because of the strongly asymmetrical performance with respect to current direction, co-flowing diffusers are most desirable in situations where the current flows in one predominant direction, such as in large rivers.

### Tee Diffuser ($\alpha \sim 0^o$, $\beta \sim 90^o$, $\gamma \sim 90^o$)

One way to avoid the preferred direction of the co-flowing diffuser is to orient the diffuser pipe parallel to the predominant current direction ($\beta \sim 90^o$) resulting in a "tee" diffuser as shown in Figure 2(c). (The name is derived from the orientation of the diffuser pipe with respect to its feeder pipe.) In stagnant flow conditions the tee diffuser behaves much like a co-flowing diffuser with the major difference being the orientation. In coastal areas the fact that the momentum is directed offshore minimizes shoreline impact, but this advantage may be weighed against potential disadvantages associated with large induced currents.

In a crossflow, dilution decreases because of interaction among the individual jets and because the pressure distribution which is set up by the ambient flow limits the quantity of water which can enter from behind the diffuser. Furthermore, the temperature distribution along the diffuser is often very non-uniform making $\Delta T_{max}$ somewhat higher than the average induced temperature. A comprehensive theory for the performance of a tee diffuser in a crossflow is not available but experimental data from a number of studies has been compiled and is presented in Figure 4. The large scatter in the data can be attributed in part to differences in topography-- different bottom slopes mean different volumes of water behind the diffuser available for entrainment, while site specific coastal features can result in different local values of $\beta$ -- and differences in the resolution of $\Delta T_{max}$. (Dilutions in Figure 4 are based on the highest temperature isotherm which is plotted.) A relationship between the observed dilution in a crossflow, $S_t$, and the theoretical dilution in stagnant water, Equation (5) evaluated for $\alpha = 0$, $\gamma = 90$, is given by

$$\frac{\sqrt{H/2B_o}}{S_t} = \left[1 + \frac{5V^2H}{u_o{}^2B_o}\right]^{1/2} \qquad (9)$$

A disadvantage of this type of diffuser is that dilution appears to decrease monotonically with crossflow velocity, V. Whereas with other basic designs the "worst case" situation is well-defined (V=0), the maximum current at a site can only be defined statistically, and the worst case performance of a tee diffuser depends on the statistical definition. For instance the maximum induced temperature associated with the current speed which is exceeded 10% of the time may differ significantly from the maximum temperature encountered with the (larger) current speed which is exceeded only 1% of the time. The fact that the greater turbulence associated with the higher ambient velocity will smooth out non-uniformities in the temperature distribution, and may eventually cause lower temperatures at positions downstream, points to one of the limitations inherent in using a single performance criterion (i.e., $\Delta T_{max}$) to evaluate discharge designs. Another (minor) disadvantage of a tee diffuser is that in coastal areas with a sloping bottom, a somewhat longer feeder pipe is required.

Staged Diffuser ($\alpha \sim 0$, $\beta \sim 0$, $\gamma \sim 0$)

Another diffuser design which has no preferred orientation with respect to longshore current direction is the "staged" diffuser. Although early diffuser design studies apparently ignored this concept, several staged diffusers have been designed recently for coastal regions where significant longshore currents can occur in either direction. As indicated in Figure 2(d) the diffuser works by entraining water primarily along its sides and jetting it along the diffuser axis. Thus, like the tee diffuser, an offshore current is produced which helps keep heat away from the shoreline.

In stagnant situations the flow is symmetrical with respect to the diffuser axis with the maximum induced temperatures and velocities occuring along the axis. A theory to treat this situation has been developed by extending classical jet analysis (using integrated equations and assumed transverse profiles for velocity and excess temperatures) to treat the case of a continuous source of momentum [6]. For $L/H \geq 15$, the theory predicts a constant centerline dilution near the end of the diffuser given by

$$S_s = 0.38\sqrt{\frac{H}{B_o}} \qquad (10)$$

where the factor of 0.38 reflects the choice of lateral entrainment coefficient as well as lateral velocity and excess temperature profiles. Equation (10) differs from Equation (5) for a uni-directional diffuser only by a constant and reflects the fact that both situations involve a directed source of momentum. For short diffusers, $L/H \le 15$, the flow is not fully developed and both observed and predicted dilutions are somewhat greater than those given by Equation (10). Beyond the diffuser, $y > L/2$ as defined in Figure 1, excess temperature decreases due to lateral entrainment; as with co-flowing and tee diffusers, this effect is greatest for small L/H.

Also in analogy with co-flowing and tee diffusers, the flow field along the diffuser will be fully mixed only if the local densimetric Froude number is larger than a critical value. By examining a range of experimental data, a critical value of about 2.5 is suggested [6] yielding a criterion for "shallow water" which is similar to Equation (7):

$$\frac{H}{B_o} \le 2.5^{-2/3} \; \mathbb{F}_s^{4/3} \; \approx \; 0.5\,\mathbb{F}_s^{4/3} \qquad (11)$$

A comparison of observed and predicted dilutions for situations involving shallow water and $L/H > 15$ is presented in Figure 5.

In a crossflow, dilution is observed to improve due to the partial separation of the individual plumes. For strong crossflows the dilution will approach the ratio of flows given by Equation (6) and hence will approach, but be somewhat less than, the dilution for a co-flowing diffuser. Of course the staged diffuser has the obvious advantage that its performance is independent of current direction!

### Vertical Diffusers ($\alpha \sim 90^\circ$, $\beta \sim 0^\circ$)

### Alternating Diffusers ($\beta \sim 0^\circ$, $\gamma \sim \pm 90^\circ$)

The three designs discussed previously have all involved the introduction by the diffuser of substantial horizontal momentum in order to induce entrainment flow. With the co-flowing and the tee designs, especially, the performance in an ambient current depends strongly on the orientation of the ambient flow with respect to the diffuser induced flow. A different strategy is to orient the nozzles vertically ($\alpha \sim 90^\circ$) thereby inducing no net horizontal momentum and thus reducing the directional preference. Similar overall performance, but without local hot spots immediately above the diffuser ports, may be obtained by alternating the diffuser ports ($\alpha \sim 0^\circ$, $\gamma = \pm 90^\circ$).

For large currents, the dilution downstream from the diffuser ports is given in either case by Equation (6) which follows from Equation (4) when $\cos \alpha = 0$. For smaller currents the diffuser performance (in shallow water) is governed by density-driven exchange flow [2]. The minimum dilution occurs when $V = 0$ and is given theoretically [2] by

$$S_a = \frac{(2\;\mathbb{F}_H)^{2/3}}{\mathbb{F}_s^{\;2/3}} \quad \frac{H}{B_o} \qquad (12)$$

where $\mathbb{F}_H$ is a densimetric Froude number of the exchange flow system and is a function of interfacial friction. $\mathbb{F}_H$ ranges from .25 for no friction to less than .15 for large frictional effects. As with the momentum diffusers Equation (12) is derived for conditions of shallow water given [2] by

$$\frac{H}{B_o} < 1.84(1 + \cos^2 \alpha)^2 \mathbb{F}_s^{4/3} \qquad (13)$$

Equation (12) was derived under the assumption of a uniform exchange flow in vertical planes perpendicular to the diffuser line, i.e., surface layer flow moving away from the diffuser, and an equal bottom layer flow moving toward the diffuser. Experiments conducted with nozzles oriented normal to the diffuser, $\gamma = \pm 90^\circ$, however, indicated that the entrainment flow entered predominantly from the ends of the diffuser while the mixed flow left along a path perpendicular to the diffuser as shown in Figure 2(e). This situation resulted in successive re-entrainment of the discharged water as flow migrated from the ends to the center of the diffuser and observed dilutions were considerably below those given by Equation (12). It was found that a uniform flow field could be obtained, however, and observation brought in line with Equation (12), if a non-uniform "nozzle control" was adopted as suggested in Figure 2(f). The nozzle distribution was shown theoretically to be

$$\gamma(y) = \pm\cot^{-1}\left[\frac{1}{\pi}\,\ell n\ \frac{1 + 2y/L}{1 - 2y/L}\right] \qquad (14)$$

where the ± refers to the alternating nozzles [2]. A comparison between observed and predicted dilutions is indicated in Figure 6.

## DESIGN COMPARISON

It is difficult to make a satisfactory comparison of the diffuser types because the performance measures discussed above are somewhat biased (eg., the maximum temperature predicted for a staged diffuser occurs in a narrow, relatively short region along the diffuser, while the temperature associated with the alternating diffuser is predicted for the whole near field) and, at best, address only one index of performance-- near field temperature. However, the exercise is useful in that it points out trends in the performance of the various diffuser types.

The design example considers a power plant situated near the coast. The receiving water is characterized by a straight coastline, a bottom with linear slope $\delta$, and a range of alongshore current speeds $0 < V < V_{max}$. Situations with predominantly uni-directional currents as well as those with bi-directional currents are considered. The design objective is to build a diffuser with minimum length while meeting the following constraints:

1) The diffuser should be in water of depth $H_o$ or greater, and
2) the maximum near field surface temperature rise should be less than $\Delta T_{max}$ under all conditions

Condition 2) suggests that for the alternating, staged and co-flowing diffuser the design velocity should be $V = 0$ while for the tee diffuser, the design condition should be $V = V_{max}$. The co-flowing diffuser is only considered for the case of uni-directional currents.

The required diffuser lengths for co-flowing, tee, staged and alternating diffusers under design conditions can be determined from Equations (5), (9), (10) and (12) respectively and are summarized below:

(Co-flowing)

$$L_c = \frac{2J_o \Delta T_o}{\rho c_\rho \Delta T_{max}{}^2 u_o (H_o + .5\delta L)} \tag{15}$$

(Tee)

$$L_t = \frac{2J_o \Delta T_o}{\rho c_\rho \Delta T_{max}{}^2 u_o (H_o + .5\delta L)} \quad \frac{1}{\left(1 - \frac{10V^2 \Delta T_o{}^2}{u_o{}^2 \Delta T_{max}{}^2}\right)} \tag{16}$$

(Staged)

$$L_s = \frac{6.9\ J_o \Delta T_o}{\rho c_\rho \Delta T_{max}{}^2 u_o (H_o + .5\delta L)} \tag{17}$$

(Alternating)

$$L_a = \frac{J_o}{\rho c_\rho (ag)^{1/2} 2\, \mathbb{F}_H \Delta T_{max}{}^{3/2} (H_o + .5\delta L)^{3/2}} \tag{18}$$

where $J_o$ is the plant heat rejection rate, $J_o = \rho c_\rho Q_o \Delta T_o$, and $\rho$ , $c_\rho$ and $a$ are the density, specific heat and coefficient of thermal expansion of water. Note that for the co-flowing, alternating and staged diffusers, where the diffuser extends offshore, the water depth is variable and an average value of $H = H_o + .5\delta L$ is used. For the tee diffuser the diffuser line is located in a depth of $H_o$. Also, in evaluating the alternating diffuser, $\mathbb{F}_H$ is strictly a function of water depth and diffuser length, but for this study, a constant value of .17 is used. This corresponds to a value of $\Phi = 1.0$ as defined in [2].

Equations (15), (16), (17) and (18) are presented in their particular form in order to isolate the effects of plant variables ($J_o$), condenser-cooling system variables ($\Delta T_o$ and $u_o$) and environmental variables ($V_{max}$, $H_o$ and $\Delta T_{max}$). The sensitivity of the required pipe length to each of these variables is shown graphically in Figure 7 using as base case conditions $J_o = 7 \times 10^9$ BTU/hr (corresponding roughly to a 1000 $MW_e$ nuclear unit), $\Delta T_o = 25^oF$, $U_o$ = 20 fps, $H_o$ = 25, $V_{max}$ = .5 fps, and $\Delta T_{max} = 3^oF$. Values for $\rho c_\rho$, a and $\delta$ were 62 BTU/ft$^3$- $^oF$, .0001$^oF^{-1}$ and .02 respctively. Lengths for the co-flowing diffuser are indicated by a dashed line to stress the fact that they are only considered in a uni-directional current.

Several conclusions can be drawn from this comparative study. First the momentum diffusers show similar trends with performance improving with increasing $H_o$ , $u_o$ and $\Delta T_{max}$ and decreasing with increasing $\Delta T_o$. In uni-directional currents where a co-flowing diffuser is appropriate, relatively short diffusers can be built to obtain any reasonable $\Delta T_{max}$. Conversely, if there are moderate or strong currents then the tee design requires a relatively long diffuser and for design currents $\geq$ 0.7 fps this design seems impractical for the conditions tested and the stated objective. In these cases the staged diffuser appears to be a logical choice.

The alternating diffuser generally requires a longer length than the staged diffuser in order to meet a given $\Delta T_{max}$. (And as discussed above, temperatures do not decrease below $\Delta T_{max}$ as rapidly.) However, as long as conditions of shallow water are met (Equation 13), the performance of the alternating diffuser is insensitive to either discharge velocity ($u_o$) or the combination of condenser flow rate-temperature rise ($Q_o - \Delta T_o$). This suggests that by using lower discharge velocities, the savings in pumping costs and the lower risk of mechanical damage incurred by organisms entrained in the discharge plume might outweigh the installation costs of a longer diffuser. Furthermore, the insensitivity of performance to $\Delta T_o$ suggests that the use of an alternating diffuser with a low condenser flow rate (low $Q_o$ and high $\Delta T_o$) may be desirable due to reduced entrainment and impingement losses at the cooling water intake, as well as lower pumping costs.

The plant load ($J_o$), temperature standard ($\Delta T_{max}$) and water depth ($H_o$) have less influence on the design choice. Increases in $H_o$ or decreases in $\Delta T_{max}$ favor slightly the alternating diffuser in comparison with the momentum diffusers, while an increase in $J_o$ requires a somewhat less than proportionate increase in diffuser length due to the increase in effective water depth. This latter observation suggests possible economies of scale associated with combining discharges from several generating units.

## SUMMARY

This paper has discussed the behavior of several basic types of submerged multi-port diffusers. The mechanics of each type are different. The co-flowing and tee diffusers use horizontal momentum to induce a flow behind the diffuser, while the staged diffuser relies on jet-like mixing along the sides of the diffuser; in each case dilution is controlled by the horizonzontal momentum of the discharge and buoyancy plays a secondary role. On the other hand, the dilution achieved by shallow water alternating diffusers is governed by buoyancy-driven exchange flow, and above a certain limit, the role of discharge momentum is insignificant.

The preceding example shows the sensitivity of each diffuser's performance to various plant, cooling system and environmental variables. Perhaps the most important conclusion to be drawn is that, depending on the combination of these variables and the design objectives, any of the four designs which were considered could be most appropriate in a given situation. It should be remembered, however, that this study considers primarily one performance standard-- near field temperature rise-- and that many other variables must enter into any actual design.

## REFERENCES

1. Cederwall, K., "Buoyant Slot Jets Into Stagnant or Flowing Environments," California Institute of Technology, W.M. Kech Laboratory of Hydraulics and Water Resources, Report No. KH-R-25, April 1971.
2. Jirka, G., and D.R.F. Harleman, "The Mechanics of Submerged Multi-port Diffusers in Shallow Water," M.I.T., R.M. Parsons Laboratory for Water Resources and Hydrodynamics, Technical Report No. 169, 1973.
3. Harleman, D.R.F., G. Jirka, K.D. Stolzenbach, P.J. Ryan and E.E. Adams, Heat Disposal in the Water Environment M.I.T. Press, to be published Spring 1977.
4. Adams, E.E., "Submerged Multi-port Diffusers in Shallow Water with Current," S.M. Thesis, M.I.T., Department of Civil Engineering, June 1972.
5. Lee, J., "Modeling of Uni-directional Thermal Diffusers in Shallow Water," Ph.D. Thesis, M.I.T., Department of Civil Engineering, to be published June 1977.
6. Almquist, C.W., and K.D. Stolzenbach, "Staged Diffusers in Shallow Water," M.I.T., R.M. Parsons Laboratory for Water Resources and Hydrodynamics, Technical Report No. 213, 1976.
7. Anon, "Browns Ferry Nuclear Plant," Tennessee Valley Authority, Engineering Laboratory, Norris, Tennessee, Advanced Report No. 14, 1972.
8. Anon, "Perry Nuclear Power Plant, Thermal Hydraulic Model Study of Cooling Water Discharge," Acres American Inc., Buffalo, N.Y., 1974.

9. Anon, "Niagara Mohawk Power Corporation, Nine Mile Point Nuclear Power Station, Hydraulic Model Study of Thermal Discharge," Acres American Inc., Buffalo N.Y., 1974.

10. Anon, "Postoperational Hydrothermal Survey for James A. Fitzpatrick Nuclear Power Plant-Power Authority of the State of New York (June, August, and October Surveys)," Stone and Webster Engineering Corporation, Boston, MA, 1976.

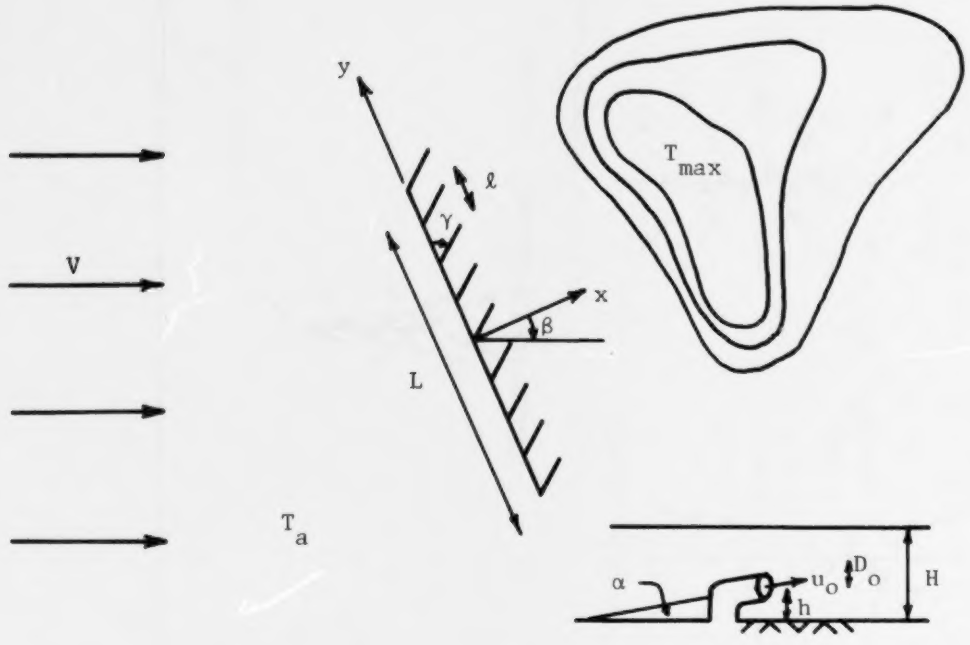
213< EEA

## Table 1

## Advantages and Disadvantages of Diffuser Designs

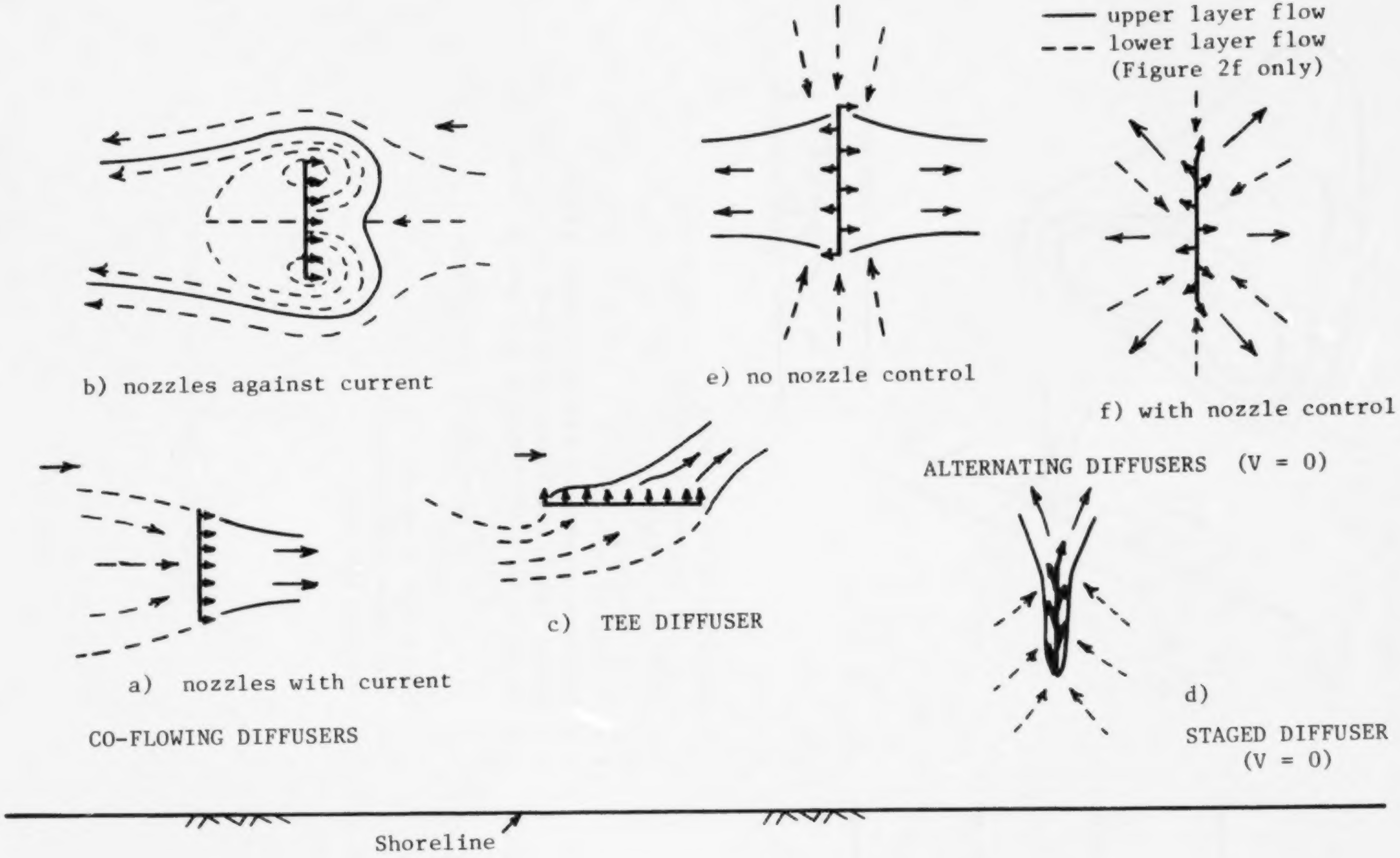
| Diffuser Types | Advantages | Disadvantages |
|---|---|---|
| Co-flowing | -- provides most efficient mixing under stagnant or co-flowing current conditions | -- poor performance in a counterflow<br>-- provides no offshore momentum* |
| Tee | -- provides efficient mixing under stagnant or nearly stagnant current conditions<br>-- provides offshore momentum* | -- poor performance in strong crossflow<br>-- difficult to define worst case (maximum current speed)<br>-- induces strong currents<br>-- may require somewhat longer feeder line |
| Staged | -- may be designed to provide acceptable dilution in worst case (stagnant current)<br>-- symmetrical performance with respect to current direction<br>-- provides offshore momentum* | -- induces strong currents |
| Alternating or Vertical | -- symmetrical performance with respect to current direction<br>-- induces lowest currents<br>-- does not require high discharge velocities | -- requires large diffuser length to obtain high dilution<br>-- provides no offshore momentum* |

*in coastal areas



$x, y$ = horizontal coordinates
$V$ = ambient current velocity
$L$ = diffuser length
$\ell$ = port spacing
$N$ = number of ports $L/\ell$
$\alpha$ = angle between port and horizontal plane
$\beta$ = angle between diffuser line and ambient current
$\gamma$ = horizontal angle between port and diffuser line
$H$ = water depth
$h$ = elevation of port above the bottom
$D_o$ = port diameter
$u_o$ = discharge velocity
$T_o$ = discharge temperature
$T_a$ = ambient temperature

Figure 1. Definition Sketch


upper layer flow
lower layer flow
(Figure 2f only)
Shoreline

b) nozzles against current

e) no nozzle control

f) with nozzle control

a) nozzles with current

c) TEE DIFFUSER

CO-FLOWING DIFFUSERS

ALTERNATING DIFFUSERS (V = 0)

d) STAGED DIFFUSER (V = 0)

Figure 2. Geometry and Flow Fields Associated with Basic Diffuser Designs

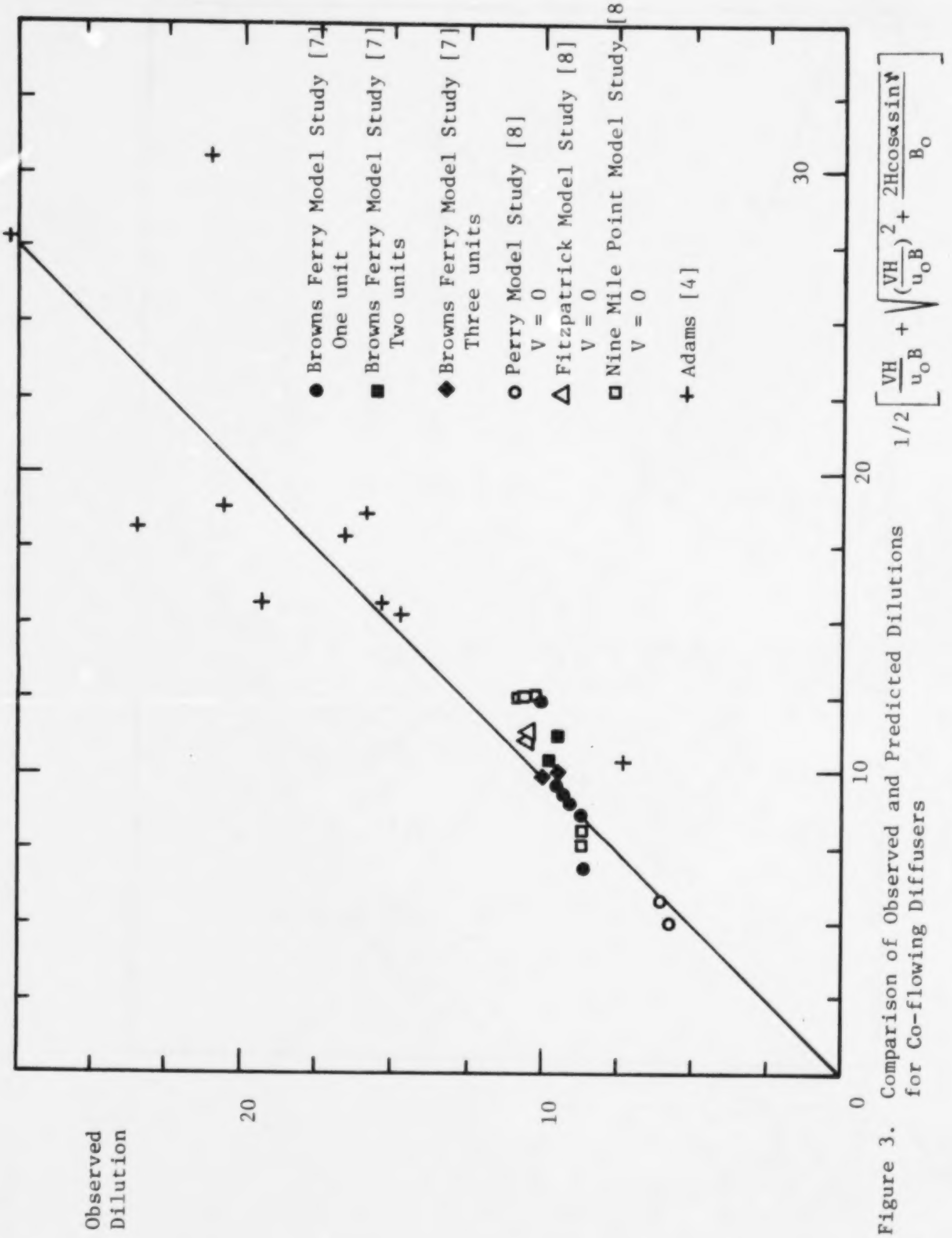


Figure 3. Comparison of Observed and Predicted Dilutions for Co-flowing Diffusers

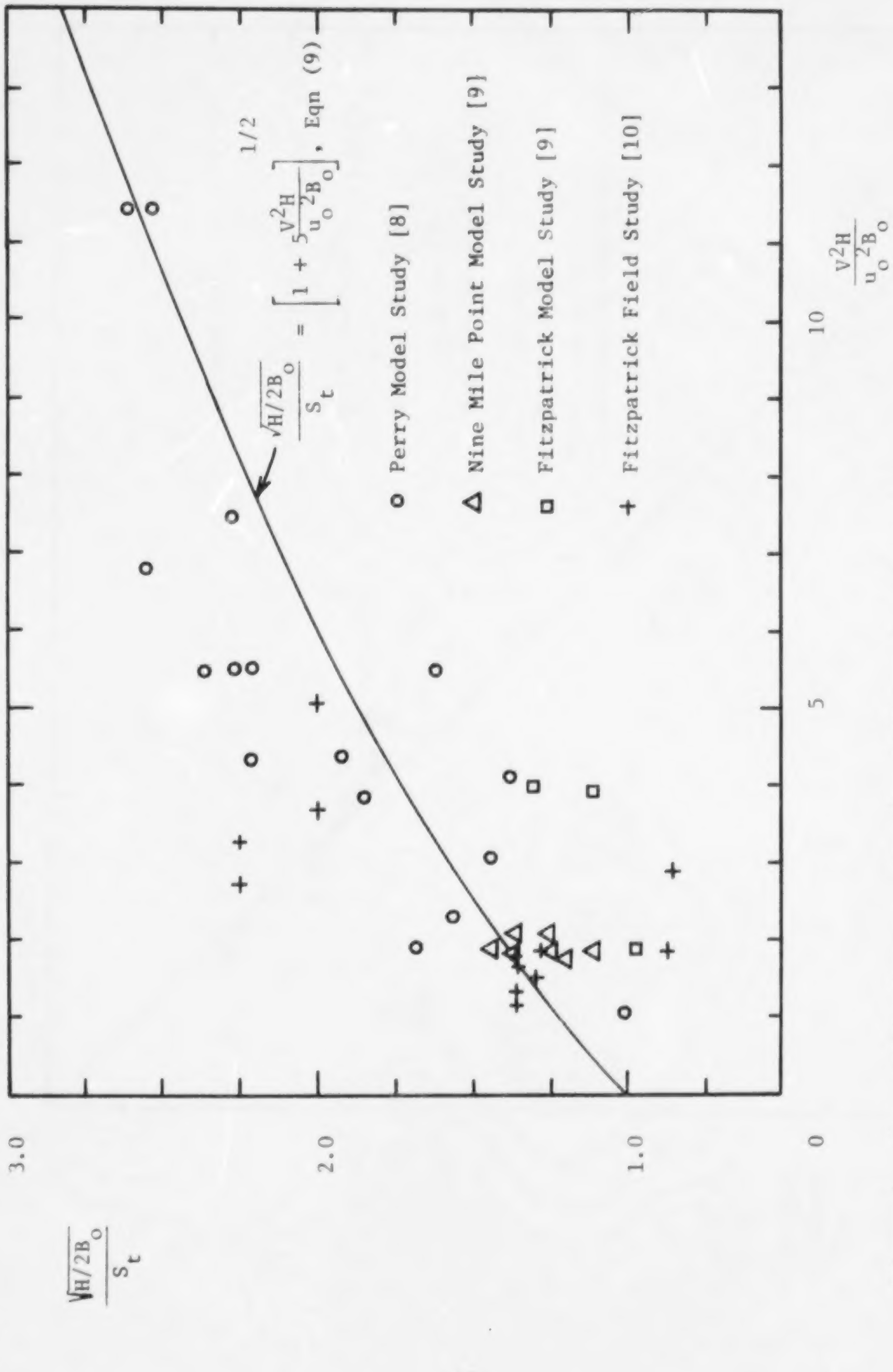


Figure 4. Observed Performance of a Tee Diffuser in a Current

217<

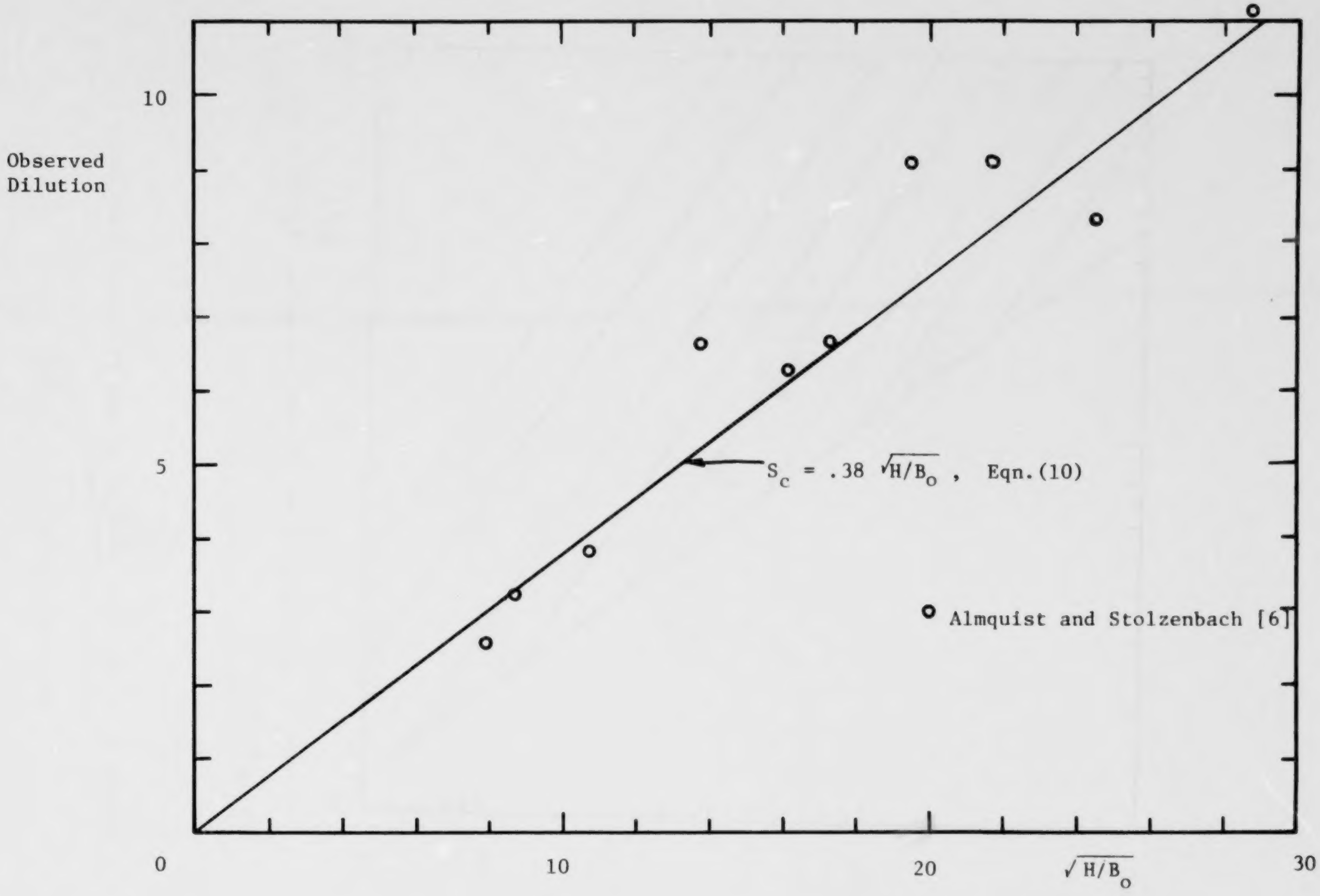


Figure 5. Comparison of Observed and Predicted Dilutions for Staged Diffusers, Adapted From [6].

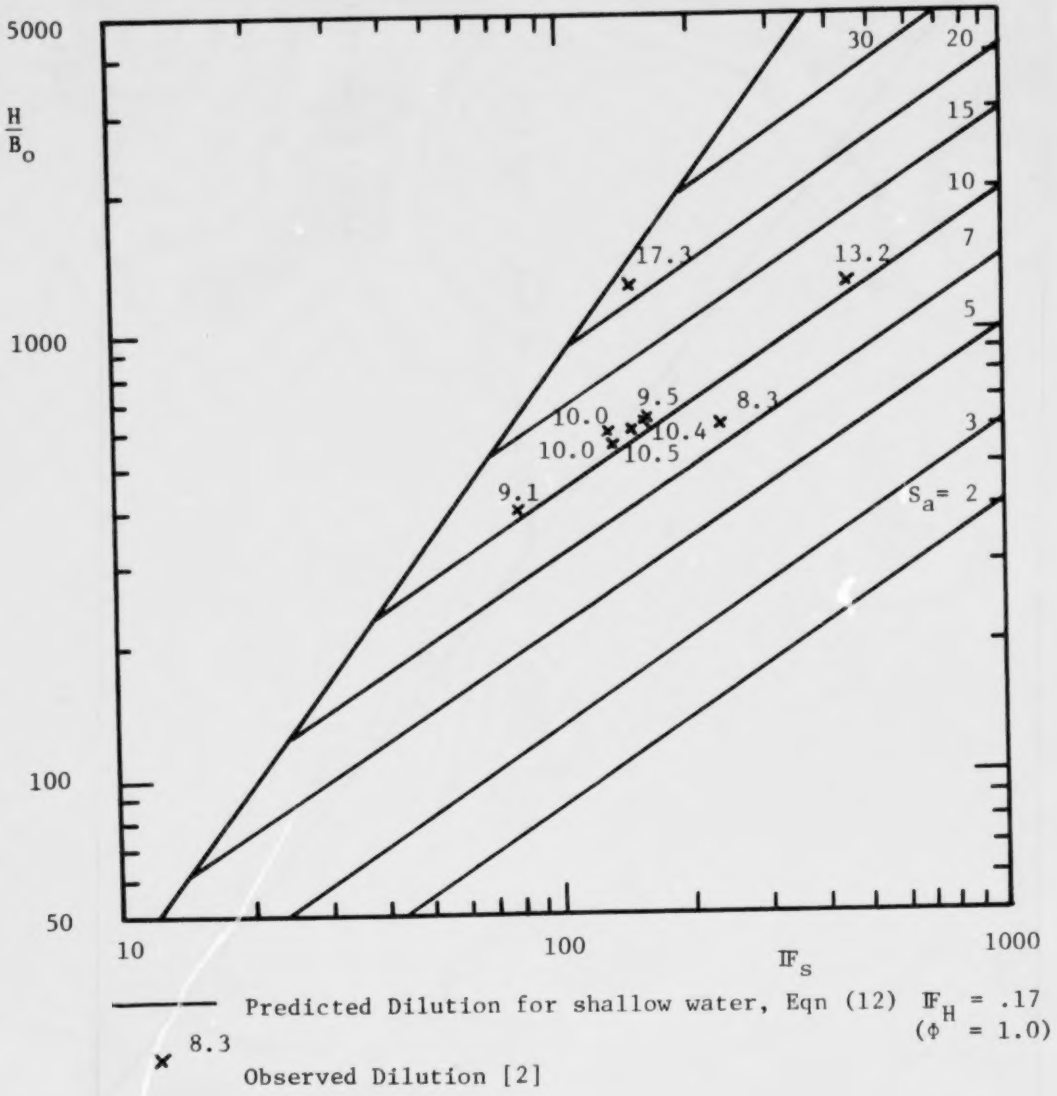
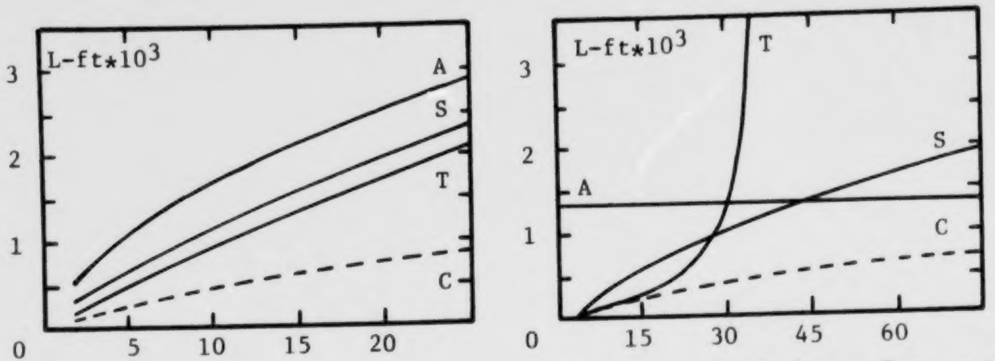


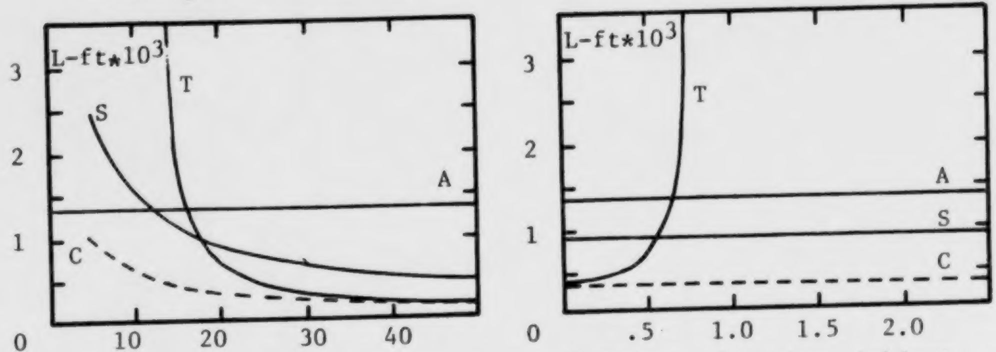
Figure 6. Comparison of Observed and Predicted Dilutions, for Alternating Diffusers

Adapted from [2]



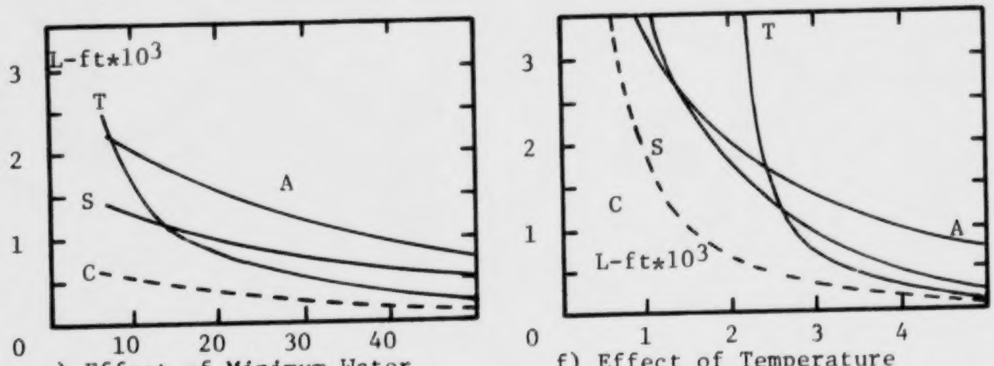
a) Effect of Heat Rejection Rate, $J_o$, in BTU/hr $*10^9$.

b) Effect of Discharge Temperature Rise, $\Delta T_o$ in $^oF$.



c) Effect of Discharge Velocity, $u_o$ in fps

d) Effect of Maximum Ambient Current Speed, $V_{max}$ in fps.



e) Effect of Minimum Water Depth, $H_o$ in ft

f) Effect of Temperature Standard, $\Delta T_{max}$ in $^oF$.

Figure 7. Sensitivity of Diffuser Length to Plant, Diffuser, and Environmental Parameters for Co-flowing (C), Tee (T), Staged (S) and Alternating (A) Diffusers. Base Case: $J_o=7 \times 10^9$BTU/hr, $\Delta T_o=25^oF$, $u_o=20$fps, $V_{max}=.5$fps, $H_o=25$ ft, $\Delta T_{max}=3^oF$. ——— valid for uni- and bi-directional currents
------ valid for uni-directional currents only

# SESSION III-A
# SOCIAL AND LEGAL ASPECTS

11-45-11

III-A- 3

# WASTE HEAT MANAGEMENT AND REGULATORY PROBLEMS

W. L. Porter
Associate General Counsel
Duke Power Company
Charlotte, North Carolina U.S.A.

## ABSTRACT

The federal and state regulation of electrical power plants is a major concern for the utility industry. The regulation of thermal discharges has required the commitment of immense resources to meet the standards while at the same time providing the utility industry with no guarantees that these commitments will remain satisfactory. The entire area of thermal regulation is in a state of flux which necessitates a constant familiarity with changing laws, regulations, and court interpretations. These burdens can be obviated by a comprehensive energy policy and a recognition that our nation must have electrical generation under compatible environmental and economic conditions.

## INTRODUCTION

There was a time--not more than six years ago--when the attorneys for a utility dealt with the usual and historical legal problems. In fact, a generating plant could almost be built without a lawyer being involved in the process. Then we progressed, some may quarrel with this word, to the point that we couldn't build a power plant without a lawyer. However, I believe we are fast approaching the point that we can't build a power plant with or without a lawyer. In fact, you might conclude that the legal-environmental business of constructing and operating generating stations is a growth industry.

I want to give John Lansche of our Legal Department credit for a major part of the work in putting these remarks together. We both deal with environmental problems including the licensing of power plants. The laws, regulations, resulting court

222<

decisions and the eight-to-ten-year period required to bring a major generating station on line, all combine to create an atmosphere of uncertainty. One of these uncertainties is thermal discharges. It is an enormous one for the utility industry because over 80% of the cooling water used by industry in our country is attributable to the generation of electric power.1/ Steam power, with its thermal wastes, is the only technology today or on the horizon which is capable of producing the bulk of electricity needed by the public. Whether one uses fossil fuels or atomic energy, we must have heat to boil water, to make steam, to drive a turbine, to turn an electric generator. When the steam has accomplished its task, it must be condensed back into water and recycled in the boiler. Thus, heat is given off which must be managed. I will attempt to relate some of the regulatory problems which the electric utility industry must solve in disposing of its heat by-product.

In order to really grasp the magnitude of today's situation, a little history might be useful. The common law doctrine of "natural flow" originally governed discharges. It required that our lakes and streams be left substantially unchanged. People could use water to satisfy their natural wants and could construct and use artificial structures so long as they did not materially affect the quantity or quality of the water. This doctrine was acceptable in its day because the industrial revolution had not yet changed the needs of society. Yet, even then, the English courts held that discharging heated water was an actionable violation of the rights of the lower riparian owners.2/ The foundation for the current miasma was thus formed.

As industrialization crept across the United States, the industrial demands on our water resources increased. The old doctrine no longer solved the problem and, so, the "reasonable use" rule was adopted in many jurisdictions. Each riparian owner under this doctrine had a right to be free *only* from unreasonable uses interfering with his reasonable use of the water. This meant that an upper riparian owner could make a reasonable use which might lower the quality or the quantity of water. This doctrine was a child of its age; it seemed to foster industrial development and mechanization; but, it began to weaken the basis for controlling pollution. Only if a water use could be deemed a nuisance was it prohibited.

The majority of courts, however, still held that a thermal discharge was actionable if the heat unreasonably interfered with the actual or proposed use of the water.3/

Demands for more energy increased with a resulting increase in waste heat. Until 1972, however, the utility industry was not governed by the mass of restrictions as it is today. The Congress had adopted laws which provided for water quality standards as the method for controlling pollution.4/ The states were required to adopt water quality standards for their interstate waters and submit them for approval to the Secretary of the Interior and later the Environmental Protection Agency (EPA). The standards were required to take into account the "use and value for public water supplies, propagation of fish and wildlife, recreational purposes, and agricultural, industrial, and other legitimate uses."5/ By 1972 all states had their required water quality standards approved. The utilities had no major compliance problems and there were a minimum of state agencies with which to deal. This statutory scheme, however, was not accomplishing its purpose; pollution was not being controlled. As historically demonstrated, a regulatory system which tests the quality of receiving water is almost impossible to enforce. All along the stream dischargers are adding to the total pollutant level; which discharger was the one which caused the stream to violate the quality standards? The states could not always be certain. This short-coming was soon realized and Congress acted. The utility industry would never be the same.

I have often heard old-timers say that they did not know that a new addition to a steam plant was planned until the construction crew arrived and started to work. Regardless of what this says about management's lack of communication, it does show the relative ease with which generating plants were built. But, the Federal Water Pollution Control Act Amendments of 1972 changed the rules of the game. A new regulatory scheme was implemented with the Environmental Protection Agency initially having enforcement authority at the federal level. Rather than using water quality standards, the Amendments created "effluent limitations" for each discharge.6/ It also created a whole new vocabulary--point-source, Best Practicable Technologies currently available, Best Available Technology, and National Pollutant Discharge Elimination System permits.

These new rules included heat as a pollutant. Instead of treating heat as a chemical discharge, the Congress, realizing heat's unique characteristics and problems, created a special exemption. Section 316(a) of the Act permits a utility to demonstrate that the effluent limitation for thermal discharges "are more stringent than necessary to assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife. . . ." If the Administrator of EPA is convinced by the demonstration, he may impose a different and less stringent thermal effluent limitation.

Also of immense importance to utilities is Section 316(b) of the Act. This section provides that one can escape the limitations of Sections 301 and 306 by demonstrating that "the location, design, construction, and capacity of cooling water intake structures reflects the best technology available for minimizing adverse environmental impacts."

In this brief discussion, I have tried to state what the law requires. But, how does federal and state regulation affect the utility industry in practice? Well, it permeates every facet of a company. From top management to the equipment operator, everyone is aware that heated discharges have their own set of rules which must be followed. Duke Power Company has one attorney who deals principally with water regulatory problems, including thermal discharges. It is a full-time job trying to ascertain what the law and regulations are and advising the company on implementing them. This attorney represents both a monetary and policy commitment to full compliance with the law.

Just a few years ago, in 1969, we applied for a Certificate of Public Convenience and Necessity to construct an electric generating station consisting of two units of approximately 1100 megawatts each. The application consisted of four pages plus a verification. The notice to the public consisted of a page and one-half and the Order granting the Certificate consisted of three pages. From the filing of the application through the issuance of the Order took only two and one-half months. There was no hearing and to my recollection no other papers or documents were filed with the Commission. It is difficult to believe that this took place such a short time ago, for such will probably never again occur.

Our proposed Perkins Nuclear Station is an excellent illustration. We applied to the North Carolina Utilities Commission for a Certificate of Public Convenience and Necessity in the summer of 1975. Hearings were held by the North Carolina Utilities Commission in 1975, 1976, and 1977. Concurrently, the North Carolina Environmental Management Commission (EMC) held numerous hearings to determine if a capacity use area should be declared. A capacity use area involves restrictions on water utilization. The EMC decided in December, 1976 that such a declaration was unwarranted, but requested the North Carolina Utilities Commission to include certain limitations on the use of water for our proposed cooling towers. The North Carolina Utilities Commission thereafter issued a Certificate of Public Convenience and Necessity in February, 1977. But, that's not the end of the story. The North Carolina Environmental Management Commission's decision has been challenged in Court and the North Carolina Utilities Commission was petitioned by intervenors to withhold the Certificate. All of this demonstrates that environmental legislation coupled with an aroused and activated public can slow down the licensing of a new generating plant for years. The costs of these delays is quite large and must ultimately be shouldered by the consumer.

A major problem facing the utility industry is EPA itself. The industry is subject to uncertain policies and unreasonable interpretations of its statutory charge and resulting regulations. Compliance with its regulations is costly. Let me illustrate with a few examples.

Duke Power Company was forced to undertake a Section 316(a) demonstration for its Marshall Steam Station. I believe this 316(a) demonstration was the first in the nation. Under appropriate regulations, the four units were exempt from federal effluent guidelines but not from state water quality standards regarding the boundary of the assigned mixing zone for the thermal plume. The plume could not be contained as required, so Duke requested alternative effluent limitations. Exhaustive environmental studies of the physical, chemical, and biological effects resulting from the operation of Marshall were undertaken. Lake water temperature, water flow, and discharge temperature were monitored; field samples were taken; the two dimensional Massachusetts Institute of Technology (MIT) cooling pond model was adapted to and validated for Lake Norman to simulate the effects of both Marshall Steam Station and McGuire Nuclear Station on the lake; the photoplankton and zooplankton communities were extensively studied as were the plant community and macroinvertibrates; lastly, extensive fish studies were conducted. Specialists from various agencies and institutions, including Johns Hopkins University, North Carolina Wildlife Resources Commission, University of North Carolina, and Massachusetts Institute of Technology, were employed to prepare some studies beginning as early as 1965 and some continuing to the present. The completed investigation demonstrated that the effect of the heated discharge from Marshall Steam Station was such that the protection and propagation of a balanced indigenous aquatic community in Lake Norman was assured. Duke, therefore, requested in June, 1975, the thermal effluent limitations in the permit be modified to conform to the alternate thermal effluent limitations described in our document. A public hearing was held in July, 1975. After all of this work, EPA did not assent to the demonstration until March, 1976. It took nine months for the bureaucracy to act.

I believe this entire exercise was unnecessary. Marshall was the most efficient steam plant in the nation for nine of the past eleven years. Marshall was a model station on Lake Norman for the application of cooling lake technology. Environmental studies were begun with the filling of the lake in 1962 and have continued to date. With all of this, we still had to expend many thousands of manhours and dollars pursuing a bureaucratic approval for the station. It should be noted that the most effective evidence presented at the hearing was not by Duke Power Company but by local fishermen. They presented evidence that Lake Norman was a fantastic fishery.

Another problem we face is securing the amount of water required for cooling. In the Duke Power service area, as in many regions of the country, we do not have access to large rivers, natural lakes or oceans. We must use our cooling water again and again, recycling it to a facility that will give up the water's extra warmth to the atmosphere prior to being returned to the condensers. There are only two such recycle facilities available from which to choose: a cooling tower and a man-made lake. The Environmental Protection Agency has the authority, of course, to regulate thermal discharges. At the moment, this area of regulation is in a state of flux; there is uncertainty as to what the law really is and how EPA will interpret it. We must remember, however, that the "regulators" do not always allow the type of system which is economically and/or environmentally best suited to a particular site.

The EPA Effluent Limitation Guidelines, 40 C.F.R. Part 423, which implemented Sections 301, 304, and 306 of the FWPCA, identified closed-cycle cooling as the "best available technology" (BAT) for the dissipation of discharge heat from generating units with July 1, 1981 as a compliance deadline. If this policy had become effective, the American consumer would have been forced to bear billions of dollars for compliance with these regulations for the backfitting of existing electric power plants with closed-cycle cooling. EPA's ban on the use of cooling lakes at new facilities would have produced no appreciable benefits to aquatic life, limited recreational opportunities and, thus yield virtually zero social benefits to the American people. EPA's simplistic analysis of the benefits to be produced by these tremendous expenditures has concentrated solely on the number of BTU's of heat removed from the water and has ignored the beneficial effects which this heat can produce in some water bodies as well as the mounting evidence of the amounts of fresh water which will be wasted by EPA's blind insistence on cooling towers as the required method of waste heat management for power plants. I am familiar with a number of cases where water utilization has become a critical issue and where regulating jurisdictional overlap leads to incongruous results.

A clear example is seen in Public Service Company of New Hampshire's applications before the Nuclear Regulatory Commission (NRC) and EPA for its Seabrook Nuclear Station. The plant, as designed, contemplated the use of once-through cooling. Indeed, the Initial Decision of the NRC rendered on June 29, 1976, approved the utilization of such a system. On November 9, 1976, the EPA Regional Administrator concluded that his earlier determinations sanctioning the use of once-through cooling at the Seabrook site were in error. The Regional Administrator indicated, however, that he was not now deciding whether a closed-cycle cooling system (i.e., cooling towers) was required but rather was reinstituting hearings to resolve this matter. On January 21, 1977, the NRC Appeal Board reversed its Licensing Board and directed such Board to conduct with all due expedition future proceedings related to the use of the Seabrook site with cooling towers and suspended the previously issued construction permits effective February 4, 1977. In January 1977, the NRC stayed the effectiveness of the Appeal Board Order so as to permit deliberation and oral argument before the Commission in mid-February. To date, the future of Seabrook is totally speculative and the dilemma the Applicant presently finds itself in has arisen solely because of the conflicting jurisdictions of the NRC and EPA.

Another example of a costly delay was recently the misfortune of a neighboring utility who announced in 1971 plans for a large nuclear station to be served by a man-made cooling lake. By July 1973, the Atomic Energy Commission, predecessor of the Nuclear Regulatory Commission, had completed safety and environmental reviews for construction permit. Then EPA entered the picture. EPA refused to recommend to the state that they grant the necessary thermal water quality variance, and further, if the state did not grant a variance, EPA would deny a discharge permit. As a result, the utility must equip the station with cooling towers as well as build a lake about one-half the size originally proposed. The utility must do much additional design work, make a second try for a construction permit through another safety and environmental review and more public hearings. The net result being project delays, not to mention the cost of cooling towers.

The same utility has another plant involved with EPA and thermal discharges into the Atlantic Ocean. It planned for a nuclear station utilizing a once-through cooling system. For two years it conducted along with nine states and federal agencies a broad-gauged environmental review of the cooling system pursuant to the Fish & Wildlife Coordination Act and the NEPA. As a result, it altered its plans at a cost of $42.3 million to construct a 5-1/2 mile discharge canal with an open ocean discharge. When it attempted to secure its operating license from the NRC, it found that closed-cycle cooling would have to be installed in order to secure the permit. As a practical matter, the company was forced to agree, under NEPA, to install cooling towers. Thereafter, in December, 1974, EPA issued the NPDES permit also with the cooling tower requirement, but the utility requested an adjudicatory hearing as to whether alternative thermal effluent limitations would be appropriate. Extensive legal battles followed with the adjudicatory hearing just beginning in June 1976, or over 18 months after the request. As of today, no decision has been reached. The utility has one unit operational and one scheduled to go on line this summer; it does not know from one day to the next if cooling towers will be required or if it can continue to operate once a decision is reached. To say that this situation is unconscionable is not emphatic enough.

Let me cite the experience of my own company in this regard. We now have under construction in licensing proceedings ten units totaling 12,340 MWe of nuclear generating capacity. Of that total, eight units totaling 9,980 MWe have been required by EPA to be constructed with cooling towers, including two units which had been sited on an existing cooling lake, all at a cost of $110 million dollars in addition to the cost of once-through cooling systems which will ultimately be passed on to the consumer.

This story has a tentative happy ending, however. By amassing scientific data to show that the EPA "myopic" interpretation of the water law toward cooling towers was wrong, Duke Power and some other utilities joined together to have this portion of the law struck down last year.7/ In fact, the Court held EPA's ban on the use of new and existing cooling lakes is clearly not in accordance with the Congressional Directive regarding the consumption of our water resources, and, further, that this failure to take into account water consumption may only be considered arbitrary and capricious.8/ The EPA regulations were remanded for further consideration. The EPA was directed by the Court to evaluate the total environmental impact of its regulations regarding water usage. What the outcome will be is open to conjecture; what we know, however, is that during the interim there are no regulations regarding the use of cooling lakes; today, one builds cooling lakes with the risk that EPA's regulations could be reinstated, resulting in backfitting of cooling towers. This uncertainty makes the allocation of resources and long-range planning a very difficult task. I might also add that it's extremely difficult to fish, swim or ski in a cooling tower.

Complying with environmental requirements is not cheap! It is very expensive! The National Economic Research Associates (NERA) has estimated that the capital expenditures for the electric utility industry for water and air pollution over the 1974 to 1983 period would be approximately $38 billion. Others have estimated the cost to be as high as $263 billion with annual costs as high as $66 billion. This would come to $815 per household per year.9/ My own company spent over $110 million from 1969 to 1975 for environmental compliance, and we will spend over $16 million in 1977 alone. The size of these figures tells us that compliance with environmental legislation represents a significant reordering of our national priorities which will only occur at the expense of other important objectives.

One may make the observation that Congress and the Courts have not given guidance to a comprehensive energy policy. A utility seeking to construct a generating station is subjected to the will of Congress, the Courts, and federal and state agencies, all jealous of the other's domain. Congress must set the policy that we are going to have generating stations under compatible environmental and economic conditions, and the Courts must lend decisional recognition to this policy.

## FOOTNOTES

1 Federal Environmental Law (1974), Environmental Law Institute, Robert Ferer, "Water Pollution Control," p. 712

2 *Mason* v. *Hill*, 110 English Report 692 (K.B. 1833)

3 *Cook* v. *Town of Mebane*, 191 N.C. 1, 131 S.E. 407 (1926)

4 The Water Quality Act of 1965, Pub. L. No. 89-234, 79 Stat. 903

5 Id. §5, 79 Stat. 908

6 33 U.S.C. 1251 et seq. P.L. 92-500

7 *Appalachian Power Co., et al.* v. *Train*, 9 ERC 1033, modified 9 ERC 1274 (1976)

8 Id., p. 1048

9 "Ecology's Missing Price Tag," *The Wall Street Journal,* August 10, 1976

12 - 45 - 17

III-A-15

# SOCIAL ASPECTS OF REGULATING WASTE HEAT

V.E. de Pass, C.L. Newman*, and J.P. Davis
Consolidated Edison Company of New York, Inc.
New York, N.Y.

## ABSTRACT

In order to meet thermal effluent limitations or water quality standards imposed by regulatory agencies, an electric generating utility like the Consolidated Edison Company of New York, Inc. (Con Edison) may find itself facing a mandate to construct closed-cycle cooling systems (e.g. cooling towers). The alternative to cooling towers, which dispose of the waste heat directly to the air rather than to the water, is to utilize the waste heat for a beneficial purpose. However, the beneficial use of this waste heat in the form of steam, for example, becomes economically feasible only when the population density is high in the near vicinity of the generating plant and there is a balance between the steam extracted for export at a high energy level and the concurrent need for electricity. It is not practical to talk about beneficial uses of the waste heat from fully expanded steam produced by a power plant for such purposes as aquaculture, greenhouses, home heating or low temperature difference engines unless a large concentration of such uses can be located immediately adjacent to the power plant. Even under such ideal conditions, the economics of utilizing such low energy level heat are questionable unless land costs, taxes and competitive utilization of available land are minimal.

---

* Now Senior Vice President, Treadwell Corporation, New York, N.Y.

## INTRODUCTION

The year 1977 will undoubtedly be a critical one for developing a long term national energy policy. It is likely that the laws written to protect the natural environment will be reviewed to determine if amendments to such legislation might result in the desirable conservation or more efficient use of energy. In the private sector, we should also carefully consider whether it is feasible to devise practical and beneficial uses for discharges (e.g. heat) rather than to discard them to the environment as wastes. At the present time, it is generally not possible to utilize the waste heat from existing nuclear power plants. For these plants, it would appear that the only alternative means of disposal for the waste heat are to the water (with once-through cooling) or to the air (via a cooling tower).

## DISCUSSION

On October 18, 1972 Congress passed the Federal Water Pollution Control Act Amendments of 1972 (FWPCA or the Act). As stated in the Act it is the national goal that the discharge of pollutants into navigable waters be eliminated by 1985, and that, as an interim goal wherever attainable there be achieved by July 1, 1983, water quality which provides for the protection and propagation of fish, shellfish and wildlife and provides for recreation in and on the water. A novel concept in the FWPCA is the designation of "heat" as a pollutant.

Final thermal regulations for the steam electric power generating point source category, issued by the United States Environmental Protection Agency (EPA), require zero discharge of heat to waterways, except for 1) blowdown from existing recirculated cooling water systems and 2) small (less than 25MW) and old units. The zero discharge to waterways limitation applies to all generating plants with a capacity of 500MW or greater that began operating after January 1, 1970 and all plants greater than 25MW that began operating after January 1, 1974.[1] The thermal ban becomes effective July 1, 1981. **

EPA regional offices are currently processing applications for Section 316(a) variances. Section 316(a) of the FWPCA allows the Administrator to impose less severe alternate thermal effluent limitations than required by the regulations, if these alternate limitations will assure the protection and propagation of a balanced indigenous population of shellfish, fish and wildlife.[2] As of January 1, 1977 a total of about forty-one Section 316(a) variances had been issued by EPA.

In addition to complying with the thermal regulations discussed above, a steam-electric power plant situated on a estuary such as the Hudson River below the City of Troy in New York State, must also meet the state's thermal water quality standards and criteria. New York's thermal criteria specify the following: (a) the water temperature at the surface of an estuary shall not be raised to more than 90°F at any point. (b) at least 50 percent of the cross sectional area and/or volume of the flow of the estuary including a minimum of one-third of the surface as measured from water edge to water edge at any stage of the tide, shall

---

** These EPA regulations have been set aside and remanded to EPA for further action. Specifically, EPA has been ordered to: (1) quantify to the extent practicable the aquatic benefits of backfitting existing plants with closed-cycle systems (2) re-examine its rejection of the suggestion by the Nuclear Regulatory Commission(NRC) to exempt from any thermal backfit rule any nuclear plant whose once-through cooling system had successfully passed NRC review pursuant to the National Environmental Policy Act (NEPA) (3) re-examine its rejection of the utilities' suggestion that open ocean thermal discharges from both existing and new plants be exempt from any closed-cycle cooling rule (4) re-examine its former ban on new cooling lakes or new units on existing cooling lakes, particularly in light of water comsumption effects (5) provide a meaningful variance provision for both existing and new plants. Appalachian Power Co. v. Train, (4th Cir. 1976) not be raised to more than 4°F over the temperature that existed before the addition of heat of artificial origin or a maximum of 83°F, whichever is less. (c) from July through September, if the water temperature at the surface of an estuary before the addition of heat of artificial origin is more than 83°F an increase in temperature not to exceed 1.5°F at any point of the estuarine passageway as delineated above, may be permitted.[3]

There are, of course, several means for disposing of waste heat from a power plant, for example, evaporative cooling ponds, with and without sprays and cooling towers. But the most efficient and ecnomical cooling system is to take water from a river or lake or other body and return it directly to its source (provided that the source is cool enough to meet turbine exhaust pressure limitations). The cooling water passes through the condensers of the plant, absorbs some of the waste heat, and is returned somewhat warmer to its source (the average for Con Edison plants is approximately 15°F). At the current state of the art, light water reactor plants have greater cooling requirements per unit of generation than do conventional coal, oil or gas fired plants because of their lower steam temperatures and pressures; thus they have a somewhat less efficient steam cycle.

As an example of the impact of the multi-agency environmental licensing process on industry and society, the following case history of one generating station of one electric utility is presented. The Indian Point Nuclear Generating Station Unit No. 2 serves the New York City and Westchester County electric customers of the Consolidated Edison Company of New York, Inc. Indian Point Unit No. 2, which operates at a power level of 873 megawatts electric (MWe), is located on a 239 acre site on the eastern bank of the Hudson River, in an industrially zoned area in the Village of Buchanan in upper Westchester County, about 24 miles north of the New York City boundary line. The site also contains two other nuclear power plants, Units No. 1 and 2.

Indian Point Unit No.2 was designed and built to operate with a once-through cooling system. In December 1972, pursuant to the National Environmental Policy Act (NEPA), an extensive hearing on environmental issues regarding the impacts from once-through cooling versus closed-cycle cooling systems was initiated. In September 1973, the Atomic

Safety and Licensing Board of the Atomic Energy Commission (AEC now NRC) issued its Initial Decision for the Unit No. 2 proceeding resulting in issuance of an amendment to the Facility Operating License. This amendment allowed for full-term, full-power operation but cessation of once-through cooling by May 1, 1978. For operation thereafter, a closed-cycle cooling system was required. Another condition of that license amendment was the requirement for submittal by the Company of an environmental report on closed-cycle cooling systems. In April 1974, as a result of an appeal of the Licensing Board's determination, the Appeal Board amended the NRC Facility Operating License authorizing the full-term, full-power operation of Indian Point Unit No. 2 by delaying the date of cessation of once-through cooling until May 1,1979. [4] In January, 1977, the NRC Appeal Board once again amended the Facility Operating License by delaying the date of cessation of once-through cooling until May 1, 1980.

Concurrently, with respect to EPA licensing, in January 1973 Con Edison filed an amended NPDES discharge permit application for Indian Point Units No. 1 and 2 with the Regional Administrator of EPA. In February 1975, EPA Region II, issued to Con Edison a NPDES discharge permit for Indian Point Units No. 1 and 2 requiring operation of Unit 2 with a "no discharge of heat" limitation. The Company then requested that EPA impose alternative thermal effluent limitations for the plant pursuant to Section 316(a) of the FWPCA. In its filing, Con Edison asserted that the operating license proceeding for Indian Point Unit No. 2 before the Nuclear Regulatory Commission, though not concluded both with respect to time and the decision sought by the Company, presented a unique and comprehensive record for the 316(a) determination.[5]

But whereas the NRC had determined that a period of interim operation should be allowed to provide an opportunity to evaluate the results of Con Edison's ecological study program and to use the results of the program to make a final determination with regard to the cooling system for Indian Point Unit No. 2, EPA asserted that "closed-cycle cooling will be imposed in any case". In this case, Con Edison has been caught between disjointed regulatory requirements to the point that one of the vital units on its system faces a potential major plant modification, with all its inherent ramifications.

Of the various alternative closed-cycle cooling systems, cooling and spray ponds at Indian Point had to be eliminated from consideration because of the great surface area required. A cooling pond for Indian Point Unit No. 2 was estimated to require about 2,700 acres whereas there are only 239 acres in the entire three unit site. It was finally determined that the most practical alternative would be a natural draft wet cooling tower. A wet tower dissipates waste heat to the atmosphere by evaporation and sensible heat transfer. But by no means consider a cooling tower to be an environmental cure-all. Engineering design indicates that the optimum tower for Indian Point 2 would be a single hyperbolic structure with a 460 foot base diameter and 560 feet tall capable of cooling 600,000 gpm of water at a 74°F design wet bulb temperature and 55 percent design relative humidity. Such a structure, if built, would easily dwarf any existing structure in the Hudson River Valley diminishing the aesthetic attractiveness of the Valley. In addition, noise levels greater than ambient would occur. [6]

Since the lower Hudson River mean salinity at Indian Point ranges from about 100 ppm to 11,000 ppm, a salt deposition rate of about 3 pounds salt per acre per year could be expected with the maximum rate occuring 3 to 4 miles from the plant, despite the use of minimum drift towers. [7]

The cost estimate for the natural draft wet cooling tower system at Indian Point No. 2 is about 96 million dollars total capital cost and 30 million dollars incremental generating costs (annual levelized revenue requirements with 1975 as the base year for present worthing). Site preparation is the largest single direct capital cost because the Indian Point site is composed of exceptionally rugged and rocky terrain. The restraints of the site require extensive rock excavation and the construction of long connecting pipe runs.

The computation of annual charges must include the cost of additional power required because of the derating imposed upon Indian Point 2 by virtue of the cooling tower. Installation of a cooling tower for Indian Point Unit No. 2 would necessitate substitute power generation (1) during the downtime required to tie the cooling tower into the existing cooling system and (2) on account of derating of the net electrical output both because of thermodynamic penalty to the steam turbine due to higher turbine backpressure associated with closed-cycle operation and additional plant auxiliary power required for operation of a closed-cycle cooling system. The total derating due to the alternative cooling system evaluated at summer peak conditions is estimated to be 63 MWe for a natural draft wet cooling tower.[8]

Aside from the dollar implications of derating probably of even greater significance to both the industry and nation is the necessity of replacing nuclear power with fossil fueled power in order to replace the lost megawatts. For example, the downtime to tie-in the cooling tower is estimated at seven months. However, since the two months are required annually for usual maintenance and refueling, only a five month downtime was used for the evaluation. An estimated 2.5 million megawatt-hours of nuclear generation from Unit No. 2 would then be lost as a consequence of the five-month chargeable downtime and the electrical derating due to closed-cycle operation. Based on an economic dispatch model of the Con Edison system, this generation would be made up mainly by fossil fuel-fired units using 480 million gallons (approx. 11.5 million barrels) of fuel oil. It should also be noted that EPA itself has estimated that the fuel penalty associated with the thermal limitation represents approximately 44,000 barrels per day of oil nationwide.[9] Yet energy conservation and fossil fuel conservation remain major national policy objectives.

At this point, having discussed the several means available for disposing of waste heat from a power plant such as Indian Point, it would be prudent to specifically ascertain whether a practical and beneficial use for the waste heat from that particular generating station can be found. The underlying objective of such an analysis would be to locate a large concentration of these practical and beneficial uses near to the plant with the economics associated with land costs, taxes and competitive utilization of available land being favorable.

In February 1976, the City of Peekskill, a small city adjacent to the Village of Buchanan and near the plant, undertook an analysis of the re-use potential of the surplus hot water from large atomic and conventional fossil fuel electric power plants in search for an alternative to the natural draft cooling tower planned for Indian Point Unit No. 2. In that report the literature and the state of the art technology on the re-use potential for the heated water emitted as part of the cooling process of nuclear power plants was reviewed. [10] The study, in general, confirmed what previous in-house studies by Con Edison had indicated regarding the feasibility of alternate closed-cycle cooling systems.

According to the Peekskill report, the criteria for an alternative to the natural draft wet cooling tower were that it be visually acceptable and technically practical. Such a standard contrasts from most studies found in the literature to date where the emphasis has been on finding a favorable economic value for the excess heat. In any case, the re-use potential of the thermal discharge is limited because the discharge, though large in volume, averages only 10$^{\circ}$F to 20$^{\circ}$F warmer than the intake river temperature. As stated in the Peekskill report, a 1,000 megawatt plant, for example, releases enough water to heat 750 to 1500 acres of greenhouses or to de-ice over two square miles of airport runway at the rate of one inch per hour. It generates a flow of 700,000 gallons of water per minute and would need more than a 2,000 acre pond to cool the water after it left the condenser. The problem however, is that the vast amounts of heat are of very low grade.

Any proposal to use this water must take into account a further constraint, the re-use must be located fairly close to the power plant because pumping water any distance is prohibitively expensive. Proposals for the re-use of the heated water are divided into five categories: agriculture and irrigation, aquaculture and mariculture, recreation, urban services and industrial uses. Heating greenhouses, irrigating crops and warming soil are the three predominant concepts put forth for agricultural application. All of these ideas would require large amounts of land to dissipate the heat carried by the coolant water. The limited available land in the Indian Point area plus the absence of a large agricultural base excluded such proposals from the list of feasible alternatives. Aquaculture and mariculture ventures have been successfully undertaken in various parts of the world using discharged heated water. There are still many technical problems to be overcome in this type of venture though and the amount of surface area required to cool the discharged water is the same as that for a cooling pond, regardless of whether there are fish in it or not. [11]

Of the many ideas on urban uses for the surplus heat all were rejected by the Peekskill Report for a variety of reasons: airport de-fogging and de-icing, while technically feasible are expensive and may only be used infrequently. In any case, Peekskill is some distance from an airport. Snow melting by placing pipes of hot water in roadways and sidewalks were rejected because it was expensive for the small number of heavy snow days in Peekskill and its usefulness would be limited to the winter months. The literature includes several possible theories of utilizing power plants in the sewage treatment process. The emphasis, however, has been on combining processes rather than utilizing the surplus hot water from the power plant in the sewage treatment plant. The literature was also reviewed for possible industrial uses of the waste heat. It was found that most industrial and chemical processes require heated water or steam that is considerably above the normal water temperature expelled from the condenser outlet at 90°F to 120°F. This problem, compounded by the requirement that the industry be located in close proximity to the power plant, precluded an industrial alternative.

The use of the heated water for space heating has been demonstrated to be feasible in several Eurpoean cities. To achieve this however, the water must be heated to about 300°F, considerably warmer than that at Indian Point, and the system requires a network of underground pipes. The cost of putting in this infrastructure would be prohibitively expensive in anything but a new high density city. Even then, few "new communities" in the United States are being planned at the densities that would justify this type of system. Moreover, this operation is not available for nuclear power plants since, according to current NRC regulations, sites with low surrounding population density are mandatory for nuclear power stations.[12]

The Indian Point Generating Station was designed as a single purpose power plant for generating electricity only and doing so efficiently. The more efficient the plant the lower the cost to the consumer. A second type of steam generating electric plant is called a dual purpose plant. This type of plant is designed to extract the steam from the electric generating process and use it for other purposes after it has created some electricity. By avoiding the losses inherent in the condenser, better use is made of the fuel energy put into the system. When the steam extracted from the power

241<

plant is used as a saleable commodity the heat losses of condensing the steam for "closing" the electric/steam cycle are avoided. Because it is so difficult to make the required demand and cost match what is necessary to make a dual purpose plant economically feasible there are relatively few dual purpose plants in the United States. Generally speaking, a dual purpose plant must be designed as such from the beginning; a second function is not usually incorporated after the plant has been built.[13]

Con Edison's steam system (by far the largest in the country) serves the needs, winter and summer of about 1.5 million people who work or live in Manhattan. The steam heats and, in many cases, also air conditions, some 2,900 major buildings in lower and midtown Manhattan. The environmental benefits of a Con Edison district heating system --- with only a few steam production sites each equipped with efficient pollution removal equipment and discharging combustion gases through tall stacks --- versus over 2500 local combustion facility sites, many with low level chimneys is obvious.

A major portion of the Con Edison steam system is, in reality, a large total energy system. Fifty-three percent of the steam distributed in 1975 came from the exhaust of topping turbines where steam energy was first used to generate electricity. The operation of this type of system is a highly efficient way of utilizing fuel, due to the fact that exhaust steam losses to a river, normally associated with electric generation, are exhausted instead to a piping system which distributes that steam for use in heating and cooling buildings. All of the plants are located relatively close to the steam districts they serve. The longest effective distance that steam can be transmitted efficiently is about two to three miles. The small amount of energy lost as steam passes through a pipe results in a loss of pressure between the steam generation plant and the load centers. The further the distance the less the ability to maintain the design delivery pressure of 125 psig.[14] Thus the waste heat from the nuclear generating station at Indian Point, 43 miles up the river from the Battery, cannot be utilized in the Con Edison steam system.

VdP

## CONCLUSION

There is no simple solution to the problem of dissipating or utilizing the waste heat generated by single purpose steam electric power plants. The reason for this is that the large amounts of water used in the cooling process are only slightly warmer than the source from which the water was taken. The environmental benefits of not putting the waste heat from a fully expanded steam cycle into an available natural body of water are often minimal. However, there is a natural limit to how much heat can be discharged, based upon the need of the water user to not significantly affect the water body's cooling capability.

Since the waste heat from existing power plants has very limited usefulness for such purposes as aquaculture, greenhouses, home heating or low temperature difference engines, if they cannot continue to operate with once-through cooling, electric utilities must ask customers to pay millions of dollars a year for cooling towers that will decrease the reliability of the electric supply as plants are first taken out of service and then derated to allow for the towers' construction and operation, and may have a negative environmental effect. Of course research will probably continue, on a case by case basis, to determine if, for a specific power plant at a specific location, a practical and beneficial use of waste heat can be developed. For new generating stations which are still in the planning or siting phases of development, in contrast to existing plants, there is a far greater potential for incorporating a second function into the plant which practically and beneficially utilizes the waste heat. In any case, the total abandonment of thermal standards or even the lessening of standards to the point where the public's health or welfare would be threatened is obviously not in the nation's best interest. It is necessary, though, to ask that the concern for the environment be balanced with a concern for the cost, reliability and availability of energy.

## REFERENCES

1. de Pass, Vincent E., "Thermal Discharges and the Law: An Engineer's Viewpoint", Proceedings of the Third National Conference on Energy and the Environment, September, 1975, p. 144-146.

2. Id.p. 147-148.

3. New York State Department of Environmental Conservation, Classifications and Standards Governing the Quality and Purity of Waters of New York State (Part 704, Official Compilation of Codes, Rules and Regulations).

4. de Pass, Vincent E., "Nuclear Power for an Urban Center" Proceedings of the Eleventh Intersociety Energy Conversion Engineering Conference, September,1976, p. 1696-1697.

5. Id. p. 1698.

6. de Pass, Vincent E., "Energy vs. the Environment in an Urban Center", Proceedings of the Ninth Intersociety Energy Conversion Engineering Conference, August, 1974, p. 517.

7. Id. p. 518.

8. de Pass, Vincent E., "Energy Conservation in an Urban Center", Proceedings of the Tenth Intersociety Energy Conversion Engineering Conference, August, 1975, p.698-699.

9. Id. p. 700-701.

10. Haney, Joyce, "A Search for Alternatives to the Proposed Cooling Towers at Indian Point", report submitted to the City of Peekskill's Community Development Agency, February 27, 1976, p. 1.

11. Id. p. 3-4.

12. Id. p. 5.

13. Id. p. 23.

14. Consolidated Edison Company of New York, Inc., "NYSERDA Integrated Public Utility", report prepared for the New York City Department of City Planning, May 28, 1976.

## ACKNOWLEDGEMENT

The coauthors wish to thank Messrs. John D. O'Toole, John J. Grob, Jr. and Michael Blatt of Engineering for their recommendations and guidance and Ms. Patricia Melograne for her secretarial assistance during the preparation of this paper.

## FIGURES

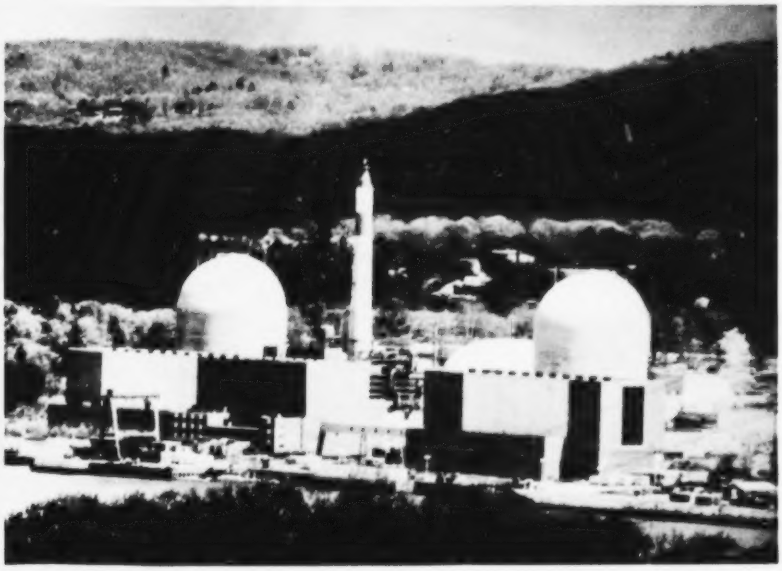


Figure 1. Con Edison's Indian Point Unit No. 2, which operates at a power level of 873 megawatts electric (MWe), is located on a 239 acre site on the eastern bank of the Hudson River in upper Westchester County, about 24 miles north of the New York City boundary line.

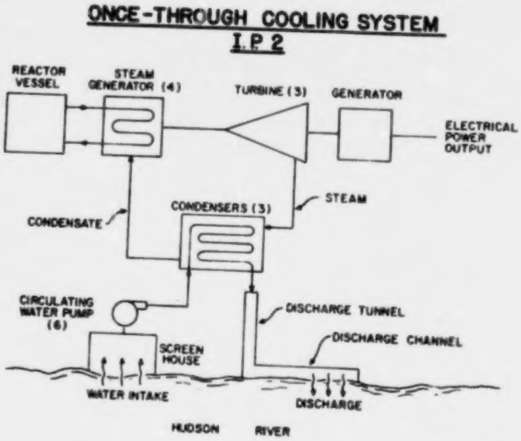

ONCE-THROUGH COOLING SYSTEM
I.P 2
REACTOR VESSEL
STEAM GENERATOR (4)
TURBINE (3)
GENERATOR
ELECTRICAL POWER OUTPUT
STEAM
CONDENSERS (3)
CONDENSATE
CIRCULATING WATER PUMP (6)
DISCHARGE TUNNEL
DISCHARGE CHANNEL
SCREEN HOUSE
WATER INTAKE
DISCHARGE
HUDSON RIVER

Figure 2. Indian Point Unit No. 2 was designed and built to operate with a once-through cooling system. In a once-through cooling system water is taken from a river or lake or other body and returned directly to its source after passing through the plant's condensers where heat is absorbed.

Figure 3. Of the various alternative closed-cycle cooling systems, cooling and spray ponds at Indian Point had to be eliminated from consideration because of the great surface area required. A cooling pond for Indian Point Unit No. 2 was estimated to require about 2,700 acres whereas there are only 239 acres in the entire three unit site.

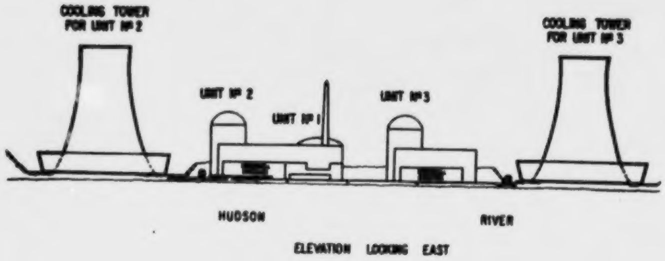

COOLING TOWER
FOR UNIT Nº 2
UNIT Nº 2
UNIT Nº 1
UNIT Nº 3
COOLING TOWER
FOR UNIT Nº 3
HUDSON
RIVER
ELEVATION LOOKING EAST

Figure 4. Engineering design indicates that the optimum tower for Indian Point 2 would be a single hyperbolic structure with a 460 foot base diameter and 560 feet tall capable of cooling 600,000 gpm of water at a 74°F design wet bulb temperature and 55 percent design relative humidity.

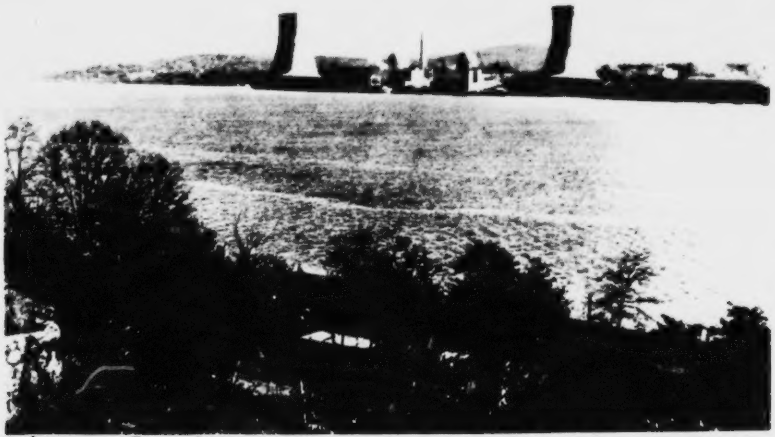


Figure 5. Shown above,is an artist's rendition of how the Indian Point site would appear if hyperbolic natural draft cooling towers are installed in the Hudson River Valley.

Figure 6. At the current state of the art, light water reactor plants (such as Indian Point Unit No. 2) have greater cooling requirements per unit of generation than do conventional coal, oil or gas fired plants because of their lower steam temperatures and pressures; thus they have a somewhat less efficient steam cycle.

Figure 7. In Con Edison's view, the present thermal component of the discharge from Indian Point Unit No.1 and 2 will "assure the protection and propagation of a balanced indigenous population of shellfish,fish, and wildlife in and on the Hudson River". Shown here is the common discharge canal for the Indian Point Generating Station.

248<

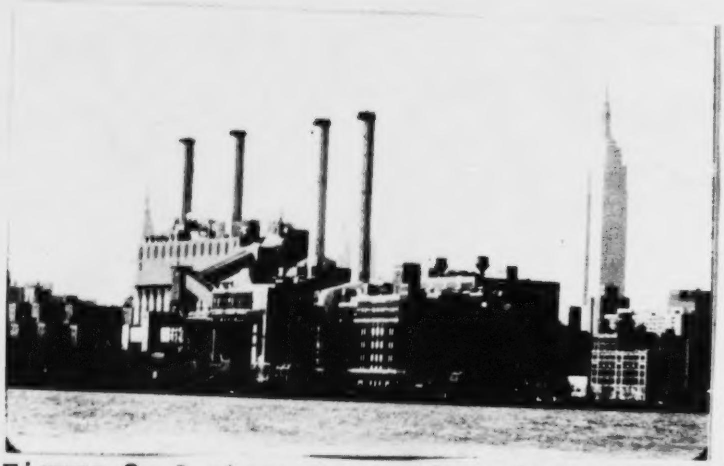


Figure 8. A steam generating electric plant such as Con Edison's East River Generating Station is called a dual purpose plant. This type of plant is designed to extract the steam from the electric generating process and to use it for other purposes after it has created some electricity.

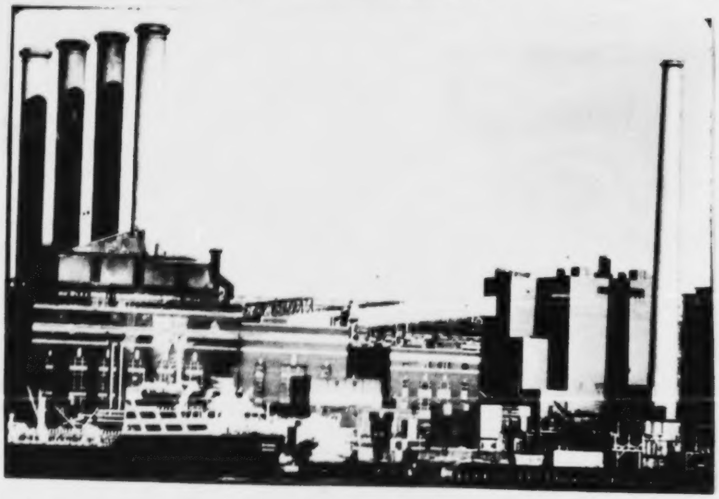


Figure 9. Con Edison's steam system (by far the largest in the country) serves the needs, winter and summer, of about 1.5 million people who work or live in Manhattan. The steam, produced in plants such as the Hudson Avenue Generating Station, heats and in many cases, also air conditions some 2,900 major buildings in lower and midtown Manhattan.

III-A-33

# SOCIAL ASPECTS OF THERMAL DISCHARGES FROM POWER PLANTS

R. S. Thorsell
Edison Electric Institute
New York City, New York

250<

OMIT

# SCIENTISTS, ENGINEERS AND LAWYERS: EXPERTISE IN ADVERSARY PROCEEDINGS

B. S. Shanoff
U.S. Environmental Protection Agency*
Washington, D.C., U.S.A.

Environmental decision-making involves complicated scientific and technological considerations that often generate controversies of a very specialized and technical nature. These controversies are shaped and determined in formal proceedings conducted by administrative agencies such as the Environmental Protection Agency and the Nuclear Regulatory Commission, where the licensing of industrial and energy facilities requires the professional judgment and opinion of experienced and highly-qualified scientists, engineers and other technical specialists. In these proceedings the relevant considerations are such that reasonable persons of necessary and sufficient expertise may be expected to differ on the completeness or accuracy of data and information, the relevant assumptions to be made, and/or the reasonable and appropriate judgments, opinions and inferences to be drawn.

Administrative agencies are often required by statute to resolve certain issues in their licensing proceedings by conducting "on the record" hearings. These trial type proceedings, with their parades of expert witnesses giving direct testimony and opposing lawyers conducting cross-examination, yield literally tons of written material. In fact, most of EPA's adjudicatory hearing records contain such enormous amounts of technical data and conflicting expert opinion on the issues that they are almost incomprehensible to a non-expert. And even after long and careful study of background material, there is considerable risk of inaccuracy. With each of our hearings it becomes more and more apparent that the traditional method of proof, when applied to complex technological and scientific issues, is cumbersome, unnecessarily time-consuming and uncertain, at best, in its results. Unfortunately, in our lawyer-dominated society, it is unlikely that such issues will be allowed to be resolved by any other means.

---

*The author does not intend to express or imply official support of the U.S. Environmental Protection Agency for the views set forth herein.

While lawyers clearly recognize and accept the need for scientific expert opinion within the legal system, scientists seem to view the legal system with unhealthy skepticism. Some believe the legal system is strangling science, distorting it into something unpleasant, so that science can be "saved" only by throwing out the lawyers; others would be astonished if anyone suggested that the law might have something to offer science or that a worthwhile interchange could and should take place. But the legal system and the scientific-technological community are not incompatible. Even in a society oriented to scientific methods and technological developments, the lawyer can play a vital role in resolving conflicts. Our thought processes and work habits are distinctly similar to those of the scientist --- we both gather and arrange phenomena in the context of a specific problem; we both seek to discover and assess what is relevant in a given problem and to discard what is not; we both attempt to predict future occurrences by relating phenomena and behavior to some rational pattern; most important, perhaps, we both believe it is possible and important to reduce (or eliminate where possible) the effects of chance in the behavior of phenomena and in the governing of man's conflicts and affairs.

Scientists, engineers and lawyers are divided by schooling and experience and sometimes differ in aptitudes, but the general configuration of intelligence factors and psychological make-up is probably the same in every good mind, regardless of professional affiliation. We have the same drives for freedom, security, influence and professional status, the same attraction for the known, and the same capacity for self-righteousness and intolerance. Above all, each of us is excellent at rationalizing our behavior and dressing it up amply with jargon, often fooling ourselves and sometimes others.

Much has been written about the patent weaknesses in a process which (a) provides for the presentation of specialized information to an untutored and unassisted judicial or administrative tribunal through party-selected and compensated expert witnesses and (b) imposes substantial procedural and evidentiary "impediments." The quest for greater accuracy in scientific and technological fact-finding has produced suggestions for procedural reform tending to inject a neutral element into the process. The most talked-about of these proposals is the establishment of a "science court" to resolve technical disputes involving questions of scientific fact. It is significant that despite ten years of on-again off-again consideration many crucial aspects of the proposal are unresolved. For one thing, no one --- the proponents, the opponents or the undecideds --- can seem to agree on what's wrong with existing decision-making procedures. More important, when the scheme is reduced to its bare essentials, the science court appears to be just another adversary system, susceptible to exploitation by those members of the scientific community who possess the rhetorical skills and wiles common to trial lawyers. The scientist-witness would be left in no better position than he ordinarily finds himself in judicial or administrative litigation today.

For the present, lawyers can serve the interests we represent most productively by working with scientists and engineers, assisting them with the skills necessary for a competent performance within the traditional adversary process.

Because environmental litigation is still in its formative years, the relatively few lawyers, scientists and engineers with active experience at the trial stage of a contested case can be considered pioneers. Incomplete scientific data, less-than-satisfactory statutes and regulations, and a fundamental incompatibility between the legal concept of proof and the conditions for valid scientific inferences --- are some of the major obstacles to overcome in putting together a case. Coping with them probably is not so much a function of talent as a desire to break new ground, to create precedents instead of merely following them.

Expert witnesses traditionally have had an important role in litigation where the subject matter of a controversy has been beyond the scope of the average person's experience and understanding and where the witness is, in fact, an expert in the area in which he or she testifies. Expert testimony is essentially the means by which specialized knowledge relevant to the issues becomes known and understood by the decision-maker. But an equally important function of an expert is to educate the lawyer about the problem, thus providing him with a theoretical framework, i.e. an hypothesis, within which the lawyer can construct his case. To the extent the lawyer and the expert(s) during preparation of a case can achieve an effective working relationship --- educate each other on what's important and why, and the best way to demonstrate it in a hearing --- the best case possible will be presented. Our experience in the first few adjudications under the Federal Water Pollution Control Act has taught us a considerable amount about interdisciplinary cooperation and the need for adequate preparation.

For the trial lawyer, the most important element of an administrative or judicial hearing is the record of the proceedings. The term "record" usually refers to the transcribed testimony of the witnesses for all the participants, the arguments and statements made by counsel throughout the hearing, and the exhibits admitted into evidence. The principal task of the trial lawyer is to build a complete, clear and accurate record tending to show the reasonableness and propriety of the outcome most favorable to his client. What makes the record so important is that it is, with narrow exceptions, the sole source of data, facts and professional opinion upon which the decision-maker may rely in reaching his conclusions. A trial lawyer will never reach this point in the proceeding confident in a result in favor of the interests he represents unless he has adequately prepared his case.

Every successful trial lawyer prepares written notes as far in advance of the hearing as possible. These notes vary greatly in substance and character depending upon the nature of the case, but ultimately they must be complete, reliable, and in a format allowing them to be readily usable at counsel table. This device helps the attorney assure that every essential fact will be presented. The trial notes represent an analysis of the case, identifying the critical issues and the relevant and material facts that will support the desired resolution of the issues. At the same time the attorney, no matter how familiar he thinks he is with the specialized field of knowledge affecting the case, normally will consult with one or more experts (who he may or may not use later on as witnesses) to educate himself in the subject matter and learn (or refresh his recollection of) the appropriate jargon. He also must begin to prepare a list of items of evidence needed to establish the basic facts, including any materials that may be needed by expert witnesses in the preparation of their opinions. Finally, he must designate the witnesses and exhibits by which each item of evidence will be presented. When all the witnesses and exhibits are presented and the evidence is finally in the record, the decision-maker presumably should find the facts and reach the conclusions desired by the attorney. In addition, most trial lawyers believe that in order to evaluate thoroughly the strength and weaknesses of their own case, it is mandatory to analyze and work out their opponent's case, including their anticipated responses to antagonistic theories and unfavorable evidence.

When problems arise in the preparation of witnesses for an adversary hearing, they primarily relate to the substance of the proceeding rather than to the procedure. Even though most books and articles written about litigation techniques are based upon experience derived from business transactions and personal injury lawsuits, the advice they offer is generally sound and applicable to all kinds of contested cases, even environmental ones. Lawyers often find that their experts are not professional witnesses; in fact, for many it may be the first experience in an adversary setting.

Perhaps the first hurdle to overcome in utilizing expert testimony is finding a competent expert. Lawyers usually talk to other lawyers who have had cases involving expert testimony relating to the same or similar subject matter in order to find out who has done a first-rate job. They may be referred or attracted to colleges and universities that maintain top-rated graduate programs in the particular field of expertise. Management consulting firms often are able to identify possible experts. Government agencies generally rely on their own employees or employees of other agencies but frequently contract with outside consultants to supply expert testimony. Witnesses tend to be chosen to serve on the basis of their prominence and success in their field for making the kind of judgments they will be called upon to make in the case. In addition, an expert witness must be able to articulate his ideas orally and in writing, and to think quickly and correctly under fire.

When a lawyer first interviews a potential expert, he is concerned only with whether or not the expert can help. An expert usually isn't "signed up" right away to be a witness; chances are, he or she will serve for a while merely in the status of a consultant until the lawyer can determine whether or not the expert's background, experience and familiarity with the specific subject matter of the case is such that the expert can best serve as a consultant only or also as a witness. Part of this evaluation will include a review of the expert's writing in the particular field and, whenever possible, his testimony from other cases. Nothing is more awkward than to have the rug pulled out from under an expert because of something embarrassing or inconsistent he has testified to under oath or written previously. Whenever these kinds of items are found in preparing for the hearing, it is best to formulate responses and explanations in anticipation of the other side attempting to impeach the witness by using them. If the opinions are damaging and cannot be explained, serious thought should be given to finding another witness to support the particular point or even abandoning the point entirely if it's not too critical.

As soon as possible after his services are enlisted, a prospective witness for a party involved in litigation must be advised about the issues in the proceeding and the position of each party on those issues. Attorneys representing the party for whom the witness will testify often know much more about the case than anyone else, and are able to provide a fairly comprehensive overview of the case into which the witness' testimony will fit. Counsel also should be able to provide some description of the respective styles and abilities of the attorneys for the other parties, as well as the temperament and idiosyncracies of the judge or presiding officer.

The first briefing session should be relaxed and as free from time constraints and interruptions as possible. It is a time for getting acquainted; it is important for attorneys and witnesses to understand each other and to identify the areas where help is needed most. At the end of the meeting, preliminary work assignments should be made for all participants --- attorneys and witnesses --- and another meeting scheduled. At the second briefing, the witnesses should do most of the talking. Perhaps their homework has produced questions; perhaps they can guide the attorneys in the roles set up for them.

Individual and group conferences with prospective witnesses are very important. Often, especially in complex cases of national significance, a party's witnesses may be scattered across the country. In such circumstances, witness meetings must be carefully scheduled and organized in order to maximize the available hours or days and to minimize the inconvenience of cross-country travel and interrupted work schedules. A copy of the tentative agenda for each such meeting should be sent to all participants sufficiently in advance of the meeting to allow adequate preparation. No meeting should be adjourned until specific activities or assignments for each participant have been agreed upon and deadlines established for their completion. In highly complex and protracted cases, it is advisable to develop and implement a master work plan for case preparation. Preparation is an unglamorous, tiresome chore. However, its importance cannot be over-emphasized --- it is easily 90 per cent of the job of presenting a case. Looked at another way, failure to prepare thoroughly is an invitation to clamity.

A number of administrative agencies, including the EPA, encourage and sometimes even require that direct testimony be submitted in writing. Since many cases are won or lost purely on the basis on direct testimony, this should become common practice, especially when the evidence is so complex and extensive that the ordinary pattern of question-and-answer, based on the recollection of the witness, cannot be expected to result in a full and accurate presentation.

The direct testimony of an expert witness is a four-part presentation: first, his qualifications as an expert; second, the material from which he fashions his opinion; third, the process or reasoning by which he progresses from the material at hand to his conclusion or opinion; and fourth, the conclusion or opinion. The direct examination should be designed with these four aspects in mind. The decision-maker is not interested in an expert's conclusory opinion alone, but rather, the material he uses and the reasoning he follows.

In the ordinary course the qualifications of an expert are shown by his education, professional or business experience, membership in professional societies, publications, and, to a lesser extent, previous influence of his opinion in cases in which he has testified as an expert on the subject. Of course, all these may not exist in a particular expert; a graduate engineer, for example may later become an expert in statistics. Or an expert may never have testified before. Regardless of background and experience, however, the first portion of the expert's direct testimony should be devoted to these topics.

The current trend in both administrative hearings and ordinary courtroom litigation is toward abandonment of the requirement that all of the material upon which the expert bases his opinion must appear in the record in the particular proceeding. The expert may base his opinion on any number of factors, including first-hand observation or the examination of data or facts presented to him either at or outside of the hearing. The data or facts need not even be admissible in evidence if they are of a type reasonably and customarily relied upon by experts in forming opinion or inferences on the subject. While the expert may choose not to disclose the data, facts or information underlying the opinions and inferences expressed in his direct testimony, he can be required ultimately to disclose them upon cross-examination.

Again, the process by which the expert derives his opinion from the material he uses --- his calculations, assumptions and reasoning --- is the most important and valuable feature of an expert's testimony. If the data base is sound, and the calculations, assumptions and reasoning are proper, the conclusion should be defensible; at the very least, other experts may have trouble finding fault with it.

It is no longer objectionable in many types of legal proceedings, including trials in the federal district courts, for experts to testify on the ultimate issue in a case. For example, in a proceeding under Section 316(a) of the Federal Water Pollution Control Act the ultimate issue is whether a certain thermal effluent limitation, which is less stringent than the limitation otherwise applicable to a particular point source, will assure the protection and propagation of a balanced, indigenous population of shellfish, fish and wildlife.

In preparing for an adversary hearing, the lawyer will ask a witness to start explaining things from the very beginning. It is important that the witness make no assumptions about the lawyer's understanding of the subject matter; he makes none about the witness'! The witness must be ready to define each term and explain each step he takes in forming an opinion. He will have to review every piece of technical data on which he intends to rely. Both must understand it and agree on its significance. If the attorney has formulated his hypotheses --- required in all cases which use, in whole or substantial part, scientific or technological data from which predictive inferences will be drawn --- the witness must help him find the vulnerable spots. Chances are, the lawyer is prepared to settle for a reasonable degree of scientific certainty.

When the written testimony nears final form, an initial preparation of the witness for cross-examination is very desirable. This step may suggest further changes in the draft testimony to facilitate the witness' performance on cross-examination. If he is obviously vulnerable on a particular point, it may be better to concede that point in the written testimony rather than allow opposing counsel to make a seemingly dramatic point on cross. The witness probably will be seen by the presiding officer only while under cross; this makes it essential to take every precaution to anticipate and minimize an adverse impact of cross-examination.

When the witness is confident in his direct testimony, he will cope with rigorous cross-examination more effectively. In an important and complex case there probably is no such thing as too much practice or preparation.

In administrative proceedings written direct testimony is seldom actually read into the record verbatim. Instead, the attorney usually marks it for identification as an exhibit of the party presenting the witness; direct oral examination then becomes a matter of asking the witness whether the testimony was prepared by him (or under his direction), whether he has any additions or corrections, and whether the testimony (as now amended, if appropriate) is true and correct to the best of his knowledge. At this point, the testimony is offered into evidence and admitted, subject to whatever appropriate objections opposing counsel may raise following cross-examination. The witness is then made available to opposing counsel for such cross-examination.

A trial lawyer's first instinct is not to cross-examine a witness, especially an expert. Lawyers know that experts know more about their special field and that experts can manipulate the jargon faster than the attorney can keep up. This capability of experts means power in an adversary proceeding. It can put the expert in control of the question-and-answer routine, and it makes the lawyer uncomfortable. Trials are lawyers' games, an arena where they will play among themselves for control. And while a lawyer can grin and bear it when another lawyer picks up all the marbles and walks away, he cannot and will not face a situation where there is a chance that a non-lawyer will do it.

Lawyers are skeptical about their ability to discredit an expert's testimony simply by cross-examination and to make an expert concede a major error in his direct testimony. Because experts don't like to admit that they have made a serious error, when they find themselves under the pressure of uncomfortable questioning, they invariably will find some way to talk themselves out of the situation, or at least into a jargon-filled hiding place.

Trial lawyers use cross-examination to cause the witness to repeat and elaborate an error or inconsistency so that there remains on the record no doubt whatever about what the witness has done. The testimony then becomes ready for destruction by other experts or in the briefs of counsel. If an expert is honest, intelligent and essentially unbiased, an attorney also may use cross-examination to get into the record much material which he would otherwise have to prove by some other method.

A lawyer does not and should not cross-examine an expert witness unless he knows the subject matter of the inquiry intimately, or unless he has at his side an equally well-qualified expert who can feed him questions for the witness. While the lawyer will never match the expert in all-over knowledge, he may very well know more than the expert about the particular subject matter of the cross-examination. When he doesn't however, he may try to rattle the witness with what trial lawyers call "shadow" cross-examination. The technique is designed to confuse the witness and goes this way: the lawyer states the factual situation to the expert several times, but each time he will change slightly the circumstances upon which the expert bases his opinion. After substituting certain facts, he asks the expert whether his opinion would have to change. At some point in the questioning the opinion must change. Throughout all of the interrogation, the cross-examiner is given fairly wide latitude for his questions.

A lawyer in cross-examination occasionally will ask whether the witness has discussed his testimony with anyone. There is nothing improper about a conversation between a witness and his attorney to facilitate the clear presentation of testimony. While it is unethical for an attorney to tell a witness what to say, it would be malpractice for an attorney to present a witness in a hearing unless he is sure the witness knows something about the issues in the case and unless he believes the testimony will be competent and relevant. Perhaps the most practical and immediate reason why the preparation of testimony should be ultimately the responsibility of the witness is that it is the witness, not the lawyer, who must take an oath with respect to that testimony and who must explain and defend it on cross-examination.

Witnesses must be prepared by their attorneys for the rigors of cross-examination both substantively and emotionally. Indeed, it is the attorney's responsibility to anticipate the adversary's questions and to guide the witness beforehand. The witness must learn to say so if it would be misleading or inaccurate to give an unqualified answer. He must listen to questions carefully, and not supply missing parts with assumed facts. And he should not change his manner, argue with counsel or exaggerate. Of course, the expert should know that he will be given the chance to clarify, explain, and even change his testimony on re-direct, and that he is not required to straighten out opposing counsel by argumentative answers.

Composure, bearing, and evenness of voice all have an effect upon whether a witness is believed or doubted. Despite the insolence of opposing counsel, the witness should maintain the same attitude and composure as when he is questioned by his own attorney. Irritation or anger toward opposing counsel does not benefit the witness or his cause because it tends to become an obstacle to clear thinking. In addition, the witness would do well to take his time before answering a question. While a pause allows one to collect his thoughts, it also can break the momentum of the questioning, and, more important, give the witness' attorney time to object if the question is improper. The purpose of making the objection will be subverted if the witness hastily answers a question before an objection is made.

While the questioner is obligated to ask intelligible questions, the witness is responsible for understanding those questions. He should not hestitate to ask that a question be repeated or re-phrased until he understands it. For example:

> "Are you asking me if I designed that study or is your question did I actually participate in gathering samples?"

A witness may choose to state his own interpretation of the question and then proceed to answer it:

> "If you're asking me if I designed the study, the answer is no."

On those occasions when a witness must indeed admit a damaging fact, the effect can be worsened if the witness betrays his concern by shifting about, by lowering his voice, or by being evasive. Whenever these signs occur, opposing counsel will undoubtedly exploit the give-away signal by having the damaging answer repeated again for greater effect in the record.

Despite all the preparation, however, many mistakes undoubtedly will be made by all of the witnesses, the attorneys, and the judge or hearing examiner in the course of an extensive hearing. Errors ought to be corrected as quickly as they are realized. The witness should not bother to defend errors; he should correct them before they become mired in an elaborate line of follow-up testimony.

A case rarely proceeds to trial without some vulnerability on both sides. If the witness' side loses a few points here and there, it is not necessarily fatal as long as the evidence, taken as a whole, generally favors that side. If counsel has done his preparation job thoroughly, very little will occur during the course of a trial which has not already been anticipated. There may be other witnesses or exhibits to mitigate the effect of an error or damaging admission, or the problem area may be susceptible to explanation. When one must admit a damaging fact, he should do so in a manner which does not highlight his own recognition of its injurious effect. Often, the witness' own attorney will sometimes address the point in direct testimony in order to put it out of the way, rather than wait and allow it to be drawn from the witness on cross-examination where the impact will be greater.

In those cases when a witness does not recall certain facts, his attorney is sometimes allowed to let him see a document and ask him if it refreshes his recollection. It may be a letter, report, memorandum or monograph he wrote or received; upon reading it, he may recall the facts. As long as he did have direct knowledge of those facts at one time and recalls them, he will be permitted to testify based upon the refreshed recollection. This is particularly useful in complex cases where background work has stretched over a period of several years. If an appropriate situation arises, it is best for the witness to say:

> "I'm not sure of that, but I believe there is a memorandum which, if I may see it, would help my recollection on the subject."

A witness may take to the stand a note or memorandum that contains information which he anticipates will refresh his recollection for a particular and expected line of questioning. However, any paper which the witness uses for such a purpose is subject to inspection by opposing counsel. It is important, then, for the witness to show the paper to his own attorney before testifying so that he might determine if it should be used.

A qualified expert should be familiar with authoritative treatises in his subject area. If he does not know of them, his qualifications will appear to be lacking. If he knows of them and agrees they are authoritative, he may be contradicted by something in those works. Experienced expert witnesses have learned to protect themselves from such contradiction in cross-examination by citing specific examples of why a particular treatise is controversial or why he does not agree with everything in it.

Several hours in a witness chair is an exhausting experience that generates a lot of inner tension. Many experienced cross-examiners save their most difficult questions until late in the interrogation, hoping that the witness will be tired, irritable, and likely to blurt out an answer without having carefully analyzed the question. Too often the following scenario takes place at the end of a day in trial:

> "Why did you answer that question the way you did? When we discussed that point before the hearing began, you were quite confident of the opposite conclusion."

> "I know. But after hearing the question in so many different ways, it became less important to me because I guess I was tired and confused. I figured if I gave him the answer he was looking for, I'd be finished for the day."

Any scientist or engineer who wants his judgments and opinions to be considered by decision-makers must not avoid opportunities to participate in the formal, adversary proceedings which generate the basis upon which important decisions are made. To the extent experts understand now these proceedings are conducted and learn how to "play the game," their contribution will significantly influence the outcome. Even though testifying may be a frightening experience for most people, it is possible, even likely, that a well-prepared witness will enjoy the challenge.

# SESSION III-B
# ECOLOGICAL EFFECTS II

266<

omit

III-B-53

# The Use of Biological/Chemical Investigations for Managing Thermal Effluents.

by Bo Møller, The Water Quality Institute.

## ABSTRACT

In the process of planning and managing thermal effluents three types of biological/chemical investigations are carried through. Preliminary investigations with a few sampling activities combined with already existing knowledge are used for excluding proposed power plant sites. Extensive site investigations giving an available view of species compositions, biomasses and process rates especially of the benthic composition in the discharge area are used for deciding if a given site is suitable from an environmental point of view. When the discharge of thermal effluents is started, monitoring of effluent consequences are carried through with emphasis on the benthic ecosystem. Examples of investigation programmes and results from all three types of investigations are shown.

13-45-17

III-B-55

# POWER GENERATION: EFFECTS ON THE AQUATIC ENVIRONMENT IN MASSACHUSETTS

R. A. Isaac
Massachusetts Division Water Pollution Control
Westborough, Massachusetts U.S.A.

## ABSTRACT

The effects of cooling water discharges from power plants have received widespread public and professional attention. Undoubtedly this attention will increase. For example, in Massachusetts the thermal steam generating capacity has nearly doubled in the past 7-10 years. Each new unit has a major ecological study supervised by State and Federal agencies along with the Company through administrative technical advisory committees.

The main concern has centered around finfish. Although there have been some relatively large fish kills at power plants within the Commonwealth, the report that one major kill in marine waters was attributed to thermally induced gas embolism is perhaps the most novel observation. Very few, if any, kills at plants sited on coastal waters has documented such a phenomenon.

However, in many respects concern has moved beyond the spectacular fish kills to assessing entrainment effects on plankton--especially fish larvae. Two major studies by power companies are now underway to try to assess the impact of entrainment on plankton levels and if that can be done, to at least begin to speculate on the significance relative to the ecosystem as a whole.

## INTRODUCTION

Thermal discharges from power plants have received widespread public and professional attention. In a few instances identifiable and sometimes spectacular problems involving finfish have resulted from these discharges; however, in many cases concern about entrainment effects on plankton--particularly ichthyoplankton--by large facilities has begun to rival the concern over the thermal effects on finfish. Entrainment results in mechanical, thermal and chemical (biofouling control agents) stresses.

## BACKGROUND

Since 1967 when the Massachusetts Division of Water Pollution Control was established, the thermal-steam generating capacity in the Commonwealth has increased approximately 3500 MW (e) nearly doubling the production capacity. This increase was spread over six individual units which are operating commercially now (1977). This increase does not include two pumped storage facilities (total capacity 1600 MW (e)) completed during the same period. The rate of expansion has slowed considerably with only one unit (Pilgrim Nuclear #2 - 1150 MW (e)) actively under construction now.

All of the new thermal units are at sites on coastal waters. Each has been the subject of intensive pre- and post-operational ecological studies, five of which have been supervised by administrative-technical committees composed of pertinent federal and state agencies, the company and the consultant the utility retained to conduct the investigation.

The basic philosophy of the committee approach is to optimize the time, effort and management of such studies, provide continuing review of the efforts by agencies that will be assessing the environmental impact and/or necessary permits, and to co-ordinate the review process by the many agencies involved. Details on all five studies were presented by Elwood [1]. In many respects, these studies foreshadowed the approach taken under the 1972 Amendments to the Federal Clean Waters Act (PL 92-500 Section 316), and the Massachusetts Thermal Standards are still based primarily on assessing the most sensitive water use.

The regulation of power plants and all energy related facilities in Massachusetts is just beginning to undergo further changes as a result of recent legislation. In 1973, the Massachusetts General Court passed legislation [2] "providing for the preservation and enhancement of the environment in conjunction with the siting and operation of electric power facilities for the promotion of a reliable, adequate and economical energy supply." To accomplish these goals, the Electric Power Facilities Siting Council was established. This legislation was later modified to include all major energy related facilities. In addition to siting and demand forecast review, the council received review authority in conjunction with National Pollutant Discharge Elimination System (NPDES) permits issued for proposed energy related facilities. The basic wording of the legislation allows the council to lessen restrictions within certain constraints. This last aspect of the council's power has yet to be attempted in practice and, indeed, the council is just becoming active in its overall program.

## FINFISH: POWER PLANT EFFECTS AND THEIR CONTROL

### Pilgrim Nuclear (Plymouth, Massachusetts)

Pilgrim (Figure 1) is a 650 MW (e) nuclear generating facility which has a cooling water flow of 311,000 gpm and a $\Delta T$ of 29°F. The plant is located on open coastal water in Cape Cod Bay.

The plant began commercial operation in late 1972. In the spring of 1973, a large school (estimated at 100,000 individuals) of menhaden (Brevoortia tyrannus) was noted in and just beyond the discharge canal. Fish in distress and subsequent mortalities were observed soon after the arrival of the school. Surprisingly, the fish appeared to be suffering from gas embolism, and not thermal shock as was first expected. Although gas embolism in

269<

salmonids had been observed in plunge pools at dams in the Northwest, few cases had ever been reported in the vicinity of thermal discharges; hence, it took some histological examination and close observation to confirm that gas embolism was indeed the main factor in the mortalities. Gas embolism may be pictured figuratively as a phenomenon in which dissolved gases in the blood stream come out of solution too quickly for the body to exhaust and results in bubbles in tissues as well as exophthalmia (pop-eye). The damage from these bubbles can be fatal. Gas embolism has most often been associated with super-saturation resulting from a rapid drop in pressure--such as in the plunge pools mentioned previously. Perhaps this condition is most familiar in divers who ascend too quickly and as a result suffer from the bends.* In the case of Pilgrim Nuclear, the driving force was temperature rise rather than pressure drop; in either case, a gas at saturation becomes supersaturated. The waters of Cape Cod Bay are at or even above saturation during the spring. The natural supersaturation is caused by warming of the waters as winter passes into spring. With the intake waters at 100% nitrogen and oxygen saturation, raising the temperature by 29°F from 41°F to 70°F, increases the supersaturation to about 134% at 31 ppt salinity as illustrated in Table I.

There were two smaller, but similar incidents--one in July 1974, while the other was in April 1975, and spring is suspected to be the critical time. Unfortunately for the investigation, Pilgrim was not operating in either the spring of 1974 or the spring of 1976. Possible factors causing this problem to occur in the spring include:

1. Low ambient water temperature (ca. 40°F) which may cause the thermal discharge to be attractive to the menhaden.

2. Relatively higher volumes of nitrogen and oxygen present at saturation in colder water than in warmer water. This causes a greater volume of gas to be released for a given temperature increase when starting with initially saturated water as illustrated in Table I.

3. Natural warming and/or upwelling of gas saturated sea water causing natural supersaturation of intake water.

The exact mechanism causing the bubbles to develop in fish has not been fully elucidated and may be related to one or more of the following:

1. Exposure to supersaturated water in the discharge canal itself and/or the plume area beyond the discharge.

2. Passage of a fish from low temperature (ambient about 40°F) to high temperature water causing exsolution of the gases in its system at a rate too rapid for the fish's system to exhaust. (This would be directly analogous to the bends.)*

No other occurrence of gas embolism caused by a thermal discharge in a marine area could be found in the literature. Some occurrences were reported

---

* Caisson disease

in fresh water (thermal driving force) and at hydroelectric dams in the Pacific northwest (pressure driving force).

The utility, in consultation with the Adminstrative-Technical advisory committee, issued a request for proposals to conduct bioassays on adult menhaden. The New England Aquarium was selected and its first task was to develop means of collecting and maintaining adult menhaden--something not done previously. The fish were exposed to the gas supersaturated water at various temperatures. Supersaturation was induced through compressed air and a piping system under a high static head. The results [4] were assessed on the basis of nitrogen supersaturation and, as illustrated in Table II, 50% mortality was observed after 96 hours at 115% nitrogen saturation. Tests were conducted at several temperatures as reported in Table III, while total gas supersaturation is depicted in Table IV. The final report states, "The most marked effect of temperature in gas saturation between 15°C and 25°C is that the average bubble size at the lowest temperature was twice that at 25°C. At 30°C, all experimental fish died without gas saturation."

Solutions to the problem are still being examined. Two main areas of investigation are barriers to prevent fish from entering the canal and reduction of gas supersaturation levels in the discharge. An immediate tactic was to install a net towards the terminus of the discharge canal to prevent fish from swimming up the channel. After several modifications, the net's effectiveness is reasonable, but not absolute, so that its utility is still debated. Other types of barriers besides the net have been evaluated [14] and these include: slope-side screens, rectangular vertical screens, angled screens, moving mesh barriers, and louvers. Only the slope-side screens and nets were considered practical with the net receiving preference. There remains, however, a question of the plume's impact beyond the net, or similar barrier, which would be located at the end of the discharge canal.

To control the gas saturation levels in the discharge canal, several alternatives that may be considered are:

1. Power reduction to reduce the temperature increase through the condenser system. This would not only reduce the area and temperature of the thermal plume, but it would also reduce the level of gas saturation in the cooling water.
2. Dilution of the cooling water which would again reduce the temperatures as well as gas concentrations.
3. Installation of a deepwater diffuser which would cause more rapid dilution of the effluent and probably eliminate the attraction which the current discharge apparently offers the menhaden.
4. Agitating the cooling water to reduce gas concentrations.

In the case of Pilgrim, alternatives 1, 2, and 3 were eliminated by preliminary analysis based on economics and/or engineering. Reduction of gas supersaturation levels by air agitation of the cooling water as it is being discharged was examined [5] in more detail. The report concluded that the system was technically feasible with a capital cost of $4.9 M and an annualized operation cost of $915,000.

The planned 1150 MW (e) addition to Pilgrim is to have a  T of 20°F with a cooling water flow of 765,000 gpm; this will reduce the degree of supersaturation when Unit II is operating alone or in combination with Unit I, since both units will discharge through a common channel. The lessening of the supersaturation values will not be enough to eliminate the problem, but should alleviate it.

Canal Electric - Sandwich, Massachusetts

The Canal Electric generating station is located on the southeastern side of the Cape Cod Canal (Figure 1). The plant consists of two generating units which have maximum electrical outputs of 560 megawatts each. The first unit went into commercial operation in July 1968, while the second achieved this status in the mid 1970's. The initial discharge scheme consisted of an open channel from which the effluent entered the Cape Cod Canal. The Canal experiences high tidal velocities (up to 2.7 knots) in the plant's vicinity, and this dramatically and rapidly influences the shape, direction and extent of the thermal plume. In addition, Buzzards Bay water on the western side of the canal is much warmer than Cape Cod Bay water which is on the eastern side. The combination of the high tidal velocities, thermal discharge and natural temperature variations make the area of the plant extremely dynamic. This combination did result in a problem. Menhaden would, on occasion, congregate near the plume and when the tide changed, they would sometimes be trapped in much warmer water. In addition, chlorine employed to control bio-fouling of the condenser tubes aggravated the stress. The result was several fish kills. The Massachusetts Division of Marine Fisheries, which was intimately involved with the ecological studies [6] at the site recommended among other items that the cooling water be no warmer than 90°F at the end of the discharge canal and that the total residual chlorine be limited to a maximum of 0.1 mg/l.

The Canal Electric Company agreed to construct, in conjunction with Unit II, a diffuser system that would meet the above temperature criteria. Before any substantial work could be done, another major fish kill occurred in August of 1974. The Director of the Division of Water Pollution Control, in consultation with the Division of Marine Fisheries, ordered the company to reduce load so that the discharge would not exceed 90°F. Court action ensued and while the judge ruled in favor of the Division, he added a proviso permitting violation of the restriction in emergency situations which essentially voided the 90°F limit. The company immediately undertook a program to relieve the situation until the diffuser system was ready. A large volume low head pump was secured from another utility and installed so that dilution water could be pumped from the intake area to the discharge canal as needed to maintain the 90°F limitation. This measure accomplished its goal and no doubt was at least partly responsible for avoiding further problems. The second unit and the diffuser system are both on-line now and no obvious problems have been noted since their activation. The diffuser is located in 27 feet of water (low tide) and is designed so that the thermal plume does not exceed 86°F within 15 feet of the surface. It was felt that menhaden, the species of concern, would normally be no deeper than this.

## Brayton Point, Somerset, Massachusetts

The Brayton Point Power Station (Figure 1) is the largest generating facility in New England. It consists of four units and has a total generating capacity of 1590 megawatts electrical. The plant is located at the head of Narragansett Bay in an area called Mt. Hope Bay. The whole water body is extremely productive and is considered a significant nursery area. The first generating unit became operational in 1963 while Unit 4 became commercial in 1974. Units 1-3 (total of 1115 MW(e)) with a cooling water flow of 620,000 GPM operate open cycle (i.e., once through cooling), and while Unit 4 (475 MW (e)) was initially intended to operate in a similar fashion with a cooling water flow of 260,000 GPM and a $\Delta T$ of 18°F, regulatory agencies required closed cycle operation because of the productivity and confinement of Mt. Hope Bay. This decision necessitated modifications of the unit's design even though construction had been initiated. Several cooling alternatives were considered and the only one felt to be feasible was spray cooling, even though this had never been done before on salt water. The plant's intake water ranges between 20 and 30 ppt. salinity. Field tests were conducted on different style spray modules to evaluate mechanical and thermal performances. A long loop-shaped channel was constructed to transport the cooling water from the discharge to the intake.[7] The modules were placed in the channel; the numbers and spacings were based on the field tests and mathematical model analyses. The system was activated and the suspected problems, even though they were anticipated, analyzed and provided for, were fatal. Complaints about salt drift on nearby (about 1/3 mile away) residences and vegetation were immediate; the thermal performance (i.e., cooling efficiency) was not adequate, apparently because of greater than anticipated interaction of heat from neighboring modules and possibly because the performance of individual modules was not as high as expected. These factors were aggravated by the high banks which surround the channel and obstruct cooling air currents. Salt spray not only caused complaints and damage to vegetation but also shorted out main generating units in the plant by causing arcing in the switchyard even though special insulators had been installed to cope with the problem.

The immediate solution to the problem was to arrange for fresh water from an unused municipal water line. The use of fresh water reduced the salinity of the closed cycle cooling water from 50,000 ppt to several thousand. While this measure adequately mitigated the salt drift problem, it represents only a short-term solution since the long-term availability of 4 MGD fresh water being used for make up cannot be guaranteed. The cooling shortfalls of the system do not preclude the unit's operation, although the designed output may not always be reached.

The possibility of employing secondary effluent from a wastewater treatment facility may be evaluated as a replacement for the potable water now utilized. In spite of these problems, the plant is operating reliably from an engineering standpoint, while by and large continuing to avoid serious, acute environmental problems.

The Brayton Point facility has also helped to provide interesting biological as well as engineering information. Thus far, a limited comparison of field observations at some power plants and bioassay data indicate that, at least in the case of menhaden, the thermal tolerance bioassays provide conservative estimates of survival. At the Brayton Point facility, menhaden in the discharge have been exposed to temperatures at and above 95°F for short periods of time without acute kills although some kills have occurred at the plant at other times. This fact has led to a trial thermal discharge limit of 95°F instead of 90°F as initially required in the first NPDES permit. Indeed, the plant had discharged water at 102°F at times before effluent limits were imposed; of course such temperatures were transient. The general condition of the fish in the discharge channel is not as robust as it would normally be, yet they survive.

The present population in the Brayton Point canal is a captive one since two nets in series were installed at the end of the discharge canal to prevent, or at least minimize, additional entries. The nets are similar in design to the one employed at Pilgrim. A general point to consider when employing any barriers in discharge channels is the desirability, if not the absolute need, of not sluicing intake screen backwash into the discharge channel. Indeed, screen backwash water may contain fish and other organisms that would have an increased chance of survival if not subjected to the thermal shock produced by being sluiced into the discharge. There are thus two separate reasons for sluicing intake screen backwash water to a place other than the discharge; first to avoid thermal shock for any surviving organisms, and secondly to avoid fouling a barrier, if one exists, with debris.

As part of our overall program, I would like to note that the Massachusetts Division of Water Pollution Control, through its Research and Demonstration Program 10 , contributed funds to an effort which examined various means of mathematically predicting the extent of thermal plumes from power plants located in coastal areas. The primary sponsors of the program were the Energy Research and Development Administration and several utilities. The final report [11] presents a review of many of the mathematical modeling techniques discussed in detail at this conference.

Non-Thermal Impacts

The thermal component is not the only factor affecting finfish. Cooling water systems are treated with chlorine, usually in the form of sodium hypochlorite (NaOCl), to control biological growth in the condenser systems. Fish kills in Massachusetts have often been caused by a combination of heat and chlorine. Because of this, the use of chlorine is required to be kept to a minimum, and other means of disinfection have been investigated [8] as part of requirements in NPDES discharge permits issued jointly by the U.S. Environmental Protection Agency and the Massachusetts Division of Water Pollution

274<

Control. The analysis of alternatives is still preliminary, but recirculation with chemical treatment is being investigated in more detail. After the cleaning operation, the water in the condenser tube system would be discharged to the power plant's wastewater treatment system as a means of minimizing the impacts of biofouling control on the receiving water.

Until this or other alternatives prove practical, chlorine remains the chemical agent for biofouling control. The chlorine usually has to be supplemented with recirculation of cooling water, where possible, so that the temperatures are high enough to kill mussels (Mytilus edulis) at marine sites, since the allowed chlorine dosages cannot effect the control necessary. The Cape Cod Canal study [6], begun in the late 1960's, included bioassays by the U.S. Bureau of Sport Fisheries and Wildlife's Sandy Hook Laboratory in New Jersey. These static bioassays indicated a 10 minute TLm of 0.7 mg/l total residual chlorine for juvenile menhaden. The 10 minute valve was selected because it approximated plant operating procedures. Based on a safety factor and round off, a value of 0.1 mg/l total residual chlorine in the effluent was recommended by the Division of Marine Fisheries [6] and adopted by the Massachusetts Division of Water Pollution Control for power plant discharges; this value is still employed today even though the U.S. EPA guidelines [9] permit 0.2 mg/l free residual chlorine average and 0.5 mg/l maximum. Power plants are able to function on these levels although the companies feel such relatively low concentrations necessitate more frequent physical cleanings. Only intermittent chlorination is allowed, and the general practice is to chlorinate half the condenser at a time. Single power plant units generally have two separate parts to the condenser system and thus chlorine concentrations in the cooling water effluents are reduced by at least 50% when the separate streams combine upon leaving the condenser system. If several units share the same discharge, the dilution is even greater. The monitoring point is at the end of the discharge canal.

The discharges from power plants are not the only factors affecting finfish; the intake is of concern as well. Fish can be drawn into intake bays and impinged on screens which are in place to protect the pumps and condenser system from debris. The impingement can be fatal and at some plants, this problem is the main impact involving finfish. In Massachusetts, through fortuitous good design or just good luck, fish impingement has not been a major problem. In reviewing new facilities, however, three guidelines are suggested:

1. Keep intake flush with the shoreline in order to avoid creating a fish trap.
2. Keep the intake velocity below 1'/second.
3. Provide top and/or bottom sills depending on the fish species present

## ENTRAINMENT

While the effect of a thermal discharge on adult fish remains a major concern among many dealing with power plants, this may be rivaled by concern over the effects on phyto-, zoo-, and particularly icthyoplankton. This is because losses of eggs and larvae through physical, chemical (biocides), and thermal damage caused by passage through a condenser system may ultimately affect the population of the species involved. As generating facilities utilize a greater portion of the total volume within a water body, this concern increases. The question is very complex, since determining the survival of organisms passing through the condenser system answers only one portion of the question. Indeed, this is a difficult task in and of itself when considering icthyoplankton. The main concern remains: what effect, if any, does the reduced numbers of eggs and larvae have on the population? Points to be addressed include the distribution of plankton in the water body, percentage of the total volume and plankton population pass through the condensers and finally the environmental impact of any losses.

The New England Power Company (Brayton Point Station) and Boston Edison Company (Pilgrim Nuclear Station) have initiated extensive ichthyoplankton studies on Mt. Hope Bay and Cape Cod Bay respectively. The work resulted in large measure from discussions of the administrative-technical advisory committees and both studies involve assessment of effects on phyto- and zooplankton entrained through the condenser system of the plant involved, as well as the extensive field sampling of ichthyoplankton distribution and concentrations. Concern about entrainment effects on icthyoplankton seems greater than for phyto- and zooplankton because of the shorter regenerative time of the latter two groups. The mechanisms producing these effects are chemical, thermal, and physical, with chemical effect being the most easily addressed. Biocides are often employed to reduce biological fouling in circulating water systems in both fresh and salt water areas. Biofouling generally occurs in condenser tubes and intake structures but can also occur at bar racks installed to prevent large debris from entering the intake area. Bacteria and invertebrates (both with and without shells) can be the culprits. Intermittent application of a biocide in sufficient concentration can control the soft bodied fouling organisms while low level continuous treatment is favored in areas where shell bearing invertebrates such as mussels are a problem. The objective is to prevent, or at least reduce, the number of invertebrate larvae which can set in the system because once established, they rapidly develop a shell. Only physical cleaning and "mussel cooking" (recirculating cooling water thereby raising its temperature to 105-120°F) can then remove them. Not all plants are designed to recirculate, thus precluding the universal employment of this practice. As in other water based processes, chlorine is the biocide of nearly universal choice.

Hamilton et al [12] estimated that primary productivity of cooling water at one plant in Maryland could be reduced by 91% when chlorination was being employed and that slight stimulation may occur in the absence of chlorination. No consistent reduction of primary production was detected in the vicinity of the plant discharge.

Results of subsequent studies [13] conducted for the Brayton Point Power Station appear to confirm these findings. Little or no effect on phytoplankton productivity could be detected from field or laboratory experiments designed to simulate temperature changes in the cooling water system of Brayton Point. It should be noted that where minor effects on phytoplankton were detected, some were increases and others were decreases in productivity. Zooplankton appeared to be affected only when exposed to chlorine, and the effect was negative. In both cases, the regenerative capacities of these plankton have lessened the concern about cropping effects of condenser systems. There remains the more general and difficult question of subtle, long-term impacts of heat discharge on species composition; this concern applies to the whole biological community exposed to thermal discharges.

All major power plants in Massachusetts employ intermittent chlorination to control biofouling in the condenser circulating water system (ie., cooling water). One plant originally intended to apply low level continuous chlorination for alternate 12 hour periods to each half of the condenser but have switched to intermittent treatment because the continuous method failed to control mussels with the concentrations permitted. Plants were concerned with free chlorine residuals (the most effective chlorine form for control) in the past, but are required in Massachusetts to control dosage on the basis of total residuals. As stated previously, total chlorine residuals have been restricted to 0.1 mg/l at the final discharge point under previous Massachusetts and current joint Commonwealth-U.S. EPA NPDES discharge permits for power plants in spite of the earlier referenced, less strict federal limitations. The limit of 0.1 mg/l total residual chlorine is based on work conducted as part of the environmental studies [6] performed at the Canal Electric Power Plant. Young of the year menhaden (Brevoortia tyrannus) had a TLm of 0.7 mg/l total residual chlorine after exposure time of 10 minutes (which closely approximated the duration of chlorination at that plant). A safety factor was applied and the value of 0.1 mg/l total residual chlorine was considered acceptable based on the data. It should be noted that this level is based on finfish--and predominately one species, at that. Further bioassays on chlorine and thermal toxicity at other new power plant units are being conducted on various species. All of the sites involved are marine. Also, extensive studies on the effects of chlorine in the marine system are being conducted by EPA's Narragansett laboratory in Kingston, Rhode Island.

The actual difference between total and free residual chlorine in relatively clean sea-water is suspected to be small, but actual data are just becoming available. Both monitoring the residuals and the effectiveness of treatment under current regulations are of concern to both companies and regulatory agencies. Continuous automatic monitors were designed to measure only free residuals and also seem to have a high maintenance requirement, especially in salt water. New monitors, which are suitable for salt water use, are now under testing.

## SUMMARY

In summary, the overt impacts of power plants on the aquatic environment has been minimal in Massachusetts. The long-term, subtle impacts either are not detectable yet, or do not exist. As the obvious and egregious forms of pollution are controlled, more effort must be expended in assessing chronic impacts and subtle effects of all effluents--especially those containing synthetic organic chemicals, but also including thermal discharges.

1. Elwood, John R., Thermal Pollution Control in Massachusetts Coastal Waters, Massachusetts Water Resources Commission, Division of Water Pollution Control, Publication Number 6110, 1971.

2. Massachusetts General Laws, Chapter 1232 of the Acts of 1973.

3. Sverdrup, H.U., Johnson, M.W. and Fleming, R.H., The Oceans: Their Physics, Chemistry, and General Biology, Prentice Hall, Englewood Cliffs, N.J., 1942.

4. New England Aquarium, Experimental Induction of Gas Bubble Disease in Adult Atlantic Menhaden, prepared for the Boston Edison Company, Boston, Massachusetts, Report No. 2-75, Boston, Massachusetts, February 1975.

5. Kraback, M.H., and Marcello, R.A.Jr., Yankee Atomic Electric Company, An Analysis of the Feasibility of Using Air Agitaion to Reduce Gas Saturations in Seawater at Pilgrim Nuclear Power Station, prepared for the Boston Edison Company, Boston, Massachusetts, July 1976.

6. Fairbanks, R.B., Collings, W.S., and Sides, W.T., An Assessment of the Effects of Electrical Power Generation on Marine Resources in the Cape Cod Canal, Massachusetts Department of Natural Resources, Division of Marine Fisheries, Boston, Massachusetts, March 1971.

7. Department of the Army, New England Division, Corps of Engineers, Final Environmental Statement: Addition of Unit No. 4 Brayton Point Generating Station, Waltham, Massachusetts, August 1973.

8. Marine Research, Inc., Final Report on Possible Alternatives to Chlorination for Controlling Fouling in Power Station Cooling Water Systems, Falmouth, Massachusetts, April 1976.

9. United States Environmental Protection Agency, Steam Electric Power Generating Point Source Category: Effluent Guidelines and Standards. Federal Register, V39N196, Part III, Washington, D.C., October 1974.

10. Elwood, J.R., and Isaac, R.A., Research and Demonstration Projects of the Massachusetts Division of Water Pollution Control, Westborough, Massachusetts, July 1975.

11. E G & G, Environmental Consultants, Forecasting Power Plant Effects on the Coastal Zone, prepared for the United States Energy Research and Development Administration, Division of Reactor Research and Development, Contract E(11-1)-2394, Waltham, Massachusetts, June 1976.

12. Hamilton, D.H. et al, Power Plants: Effects of Chlorination on Estuarine Primary Production, Science V.169, P 197.

13. Marine Research, Inc., Summary of Brayton Point Investigations, 1970-1976, for New England Power Company, Falmouth, Massachusetts, January 1977.

III-B-66

14. Doret, S.C., Marcello, R.A.Jr., and MacPherson, R.B., Yankee Atomic Electric Company, Evaluation of Alternative Fish Barrier Bystems for Pilgrim Nuclear Power Station, prepared for the Boston Edison Company, Boston, Massachusetts, July 1976.

NITROGEN AND OXYGEN SATURATION VALUES AT VARIOUS TEMPERATURES AND SALINITIES*
VALUES IN ml/1

TABLE I

| Chlorinity %<br>Salinity | 15<br>27.11 | | 16<br>28.91 | | 17<br>30.72 | | 18<br>32.52 | | 19<br>34.33 | | 20<br>36.11 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature °C | $N_2$ | $O_2$ | $N_2$ | $O_2$ | $N_2$ | $O_2$ | $N_2$ | $O_2$ | $N_2$ | $O_2$ | $N_2$ | $O_2$ |
| 0 | 15.22 | 8.55 | 15.02 | 8.43 | 14.82 | 8.32 | 14.61 | 8.20 | 14.40 | 8.08 | 14.21 | 7.97 |
| 5 | 13.43 | 7.56 | 13.26 | 7.46 | 13.10 | 7.36 | 12.94 | 7.26 | 12.78 | 7.16 | 12.62 | 7.07 |
| 10 | 12.15 | 6.77 | 12.00 | 6.69 | 11.86 | 6.60 | 11.71 | 6.52 | 11.56 | 6.44 | 11.42 | 6.35 |
| 15 | 11.04 | 6.14 | 10.92 | 6.07 | 10.79 | 6.00 | 10.66 | 5.93 | 10.53 | 5.86 | 10.39 | 5.79 |
| 20 | 10.08 | 5.63 | 9.98 | 5.56 | 9.87 | 5.50 | 9.76 | 5.44 | 9.65 | 5.38 | 9.54 | 5.31 |
| 25 | 9.30 | 5.17 | 9.21 | 5.12 | 9.11 | 5.06 | 9.02 | 5.00 | 8.92 | 4.95 | 8.82 | 4.86 |

* Based on work by Fox and Rakostra and Emmel as quoted in Reference [3].

## LOCATION OF GAS EMBOLI IN MENHADEN AT VARIOUS SATURATION LEVELS*

### TABLE II

| % N Saturation | Necropsy Observations | % Survival |
|---|---|---|
| 105 | No external or internal bubbles | 100%/96 hours |
| 110 | No external bubbles apparent, internal bubbles apparent only in intestines (1-3 mm) | 93%/96 hours |
| 115 | External bubbles in some or all of the fins, sometimes in eye, bubbles usually ~.5-2.0 mm. Internal bubbles in intestines and caeca only. Bubbles in intestines 3-5 mm, caeca 1-3 mm. | 50%/96 hours |
| 120 | External bubbles in some or all of fins, always in the dorsal and caudal; operculum; roof of mouth; eyes. Internal bubbles in intestines, caeca, heart, bulbous arteriosis (with distention), swim bladder distention, hemostasis of gill arterioles with melanophores present, indicating stress. Bubbles maximum ~10 mm at lower termperature and ~5 mm at higher temperatures | 0%/24 hours |
| 130 | External bubbles present in all fins, operculum, roof of mouth eyes (exophthalmia with some bursting). Internal bubbles in all organs with severe distention of bulbous arteriosis and swim bladder, along entire length of gill arterioles in most cases, hemostasis obvious with melanophores present. Bubbles maximum ~10 mm at lower temperatures and ~5 mm at higher temperatures. | 0%/24 hours |

* From Reference [4]

## GAS SATURATION VALUES AT VARIOUS TEMPERATURES DURING MENHADEN TESTING*

### TABLE III

| Water Temp. °C | % Nitrogen Saturation | % Total Saturation | % Oxygen Saturation |
|---|---|---|---|
| 30 | ALL SPECIMENS DIED | | |
| 25 | 130 | 125 | 130 |
| | 120 | 118 | 121 |
| | 110 | 107 | 112 |
| | 105 | 95 | 85 |
| 22 | 123 | 119 | 124 |
| | 115 | 108 | 91 |
| | 110 | 107 | 115 |
| | 105 | 100 | 92 |
| 15 | 130 | 126 | 134 |
| | 120 | 118 | 130 |
| | 110 | 105 | 110 |
| | 105 | 100 | 95 |

* From Reference [4]

## MENHADEN MORTALITY AT VARIOUS TEMPERATURES* AND NITROGEN SATURATION LEVELS

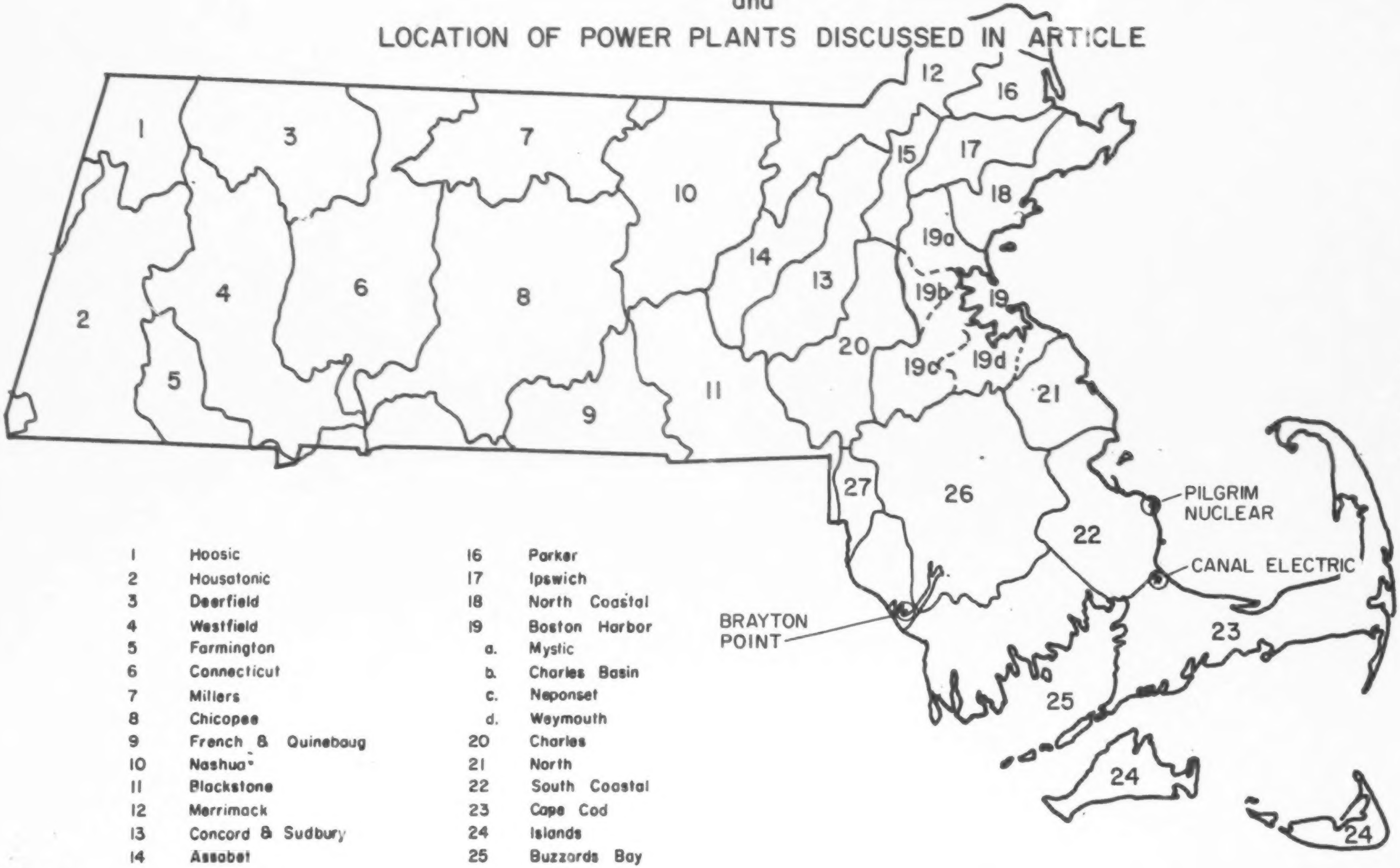
### TABLE IV

| Water Temp. C. | % Nitrogen Saturation | Mortality Day 0 | 1 | 2 | 3 | 4 | Total |
|---|---|---|---|---|---|---|---|
| 30 | 105 | 1 | 2 | 3 | | | 6 |
| 25 | 130 | 0 | 12 | | | | 12 |
| | 120 | 0 | 12 | | | | 12 |
| | 110 | 0 | 0 | 0 | 1 | 3 | 12 |
| | 105 | 0 | 0 | 0 | 0 | 2 | 18 |
| 22 | 123 | 0 | 12 | | | | 12 |
| | 115 | 0 | 0 | 2 | 2 | 2 | 12 |
| | 110 | 0 | 0 | 0 | 2 | 2 | 12 |
| | 105 | 0 | 0 | 0 | 0 | 0 | 18 |
| 15 | 130 | 11 | 1 | | | | 12 |
| | 120 | 12 | | | | | 12 |
| | 110 | 0 | 0 | 0 | 2 | 1 | 12 |
| | 105 | 0 | 0 | 0 | 0 | 0 | 18 |

* From Reference [4]

# COMMONWEALTH of MASSACHUSETTS

## DRAINAGE BASINS
## and
## LOCATION OF POWER PLANTS DISCUSSED IN ARTICLE


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19a
19b
19
19c
19d
20
21
22
23
24
25
26
27
PILGRIM NUCLEAR
CANAL ELECTRIC
BRAYTON POINT

| | |
|---|---|
| 1 | Hoosic |
| 2 | Housatonic |
| 3 | Deerfield |
| 4 | Westfield |
| 5 | Farmington |
| 6 | Connecticut |
| 7 | Millers |
| 8 | Chicopee |
| 9 | French & Quinebaug |
| 10 | Nashua |
| 11 | Blackstone |
| 12 | Merrimack |
| 13 | Concord & Sudbury |
| 14 | Assabet |
| 15 | Shawsheen |
| 16 | Parker |
| 17 | Ipswich |
| 18 | North Coastal |
| 19 | Boston Harbor |
| a. | Mystic |
| b. | Charles Basin |
| c. | Neponset |
| d. | Weymouth |
| 20 | Charles |
| 21 | North |
| 22 | South Coastal |
| 23 | Cape Cod |
| 24 | Islands |
| 25 | Buzzards Bay |
| 26 | Taunton |
| 27 | Ten Mile |

FIGURE I

284<

14-45-14

III-B-73

# AVOIDANCE OF THERMAL EFFLUENT BY JUVENILE CHINOOK SALMON (ONCORHYNCHUS TSHAWYTSCHA) AND ITS IMPLICATIONS IN WASTE HEAT MANAGEMENT

R. H. Gray
Freshwater Sciences, Ecosystems Department
Battelle Pacific Northwest Laboratories
Richland, Washington U.S.A.

## ABSTRACT

Knowledge of behavioral responses of aquatic organisms to thermal discharges at power plants is essential to evaluate thermal exposure and subsequent effects on survival and ecological success. Instantaneous responses of juvenile salmon that encountered a simulated river-thermal plume interface were assessed in a model raceway with a thermal discharge. Fish movement and response to the discharge were recorded on videotape. Juvenile chinook salmon (Oncorhynchus tshawytscha) tested under three discharge conditions (no plume, ambient plume and heated plume) avoided plume temperatures greater than 9-11°C above ambient. Fish occasionally oriented to the discharge current, but were not attracted to the thermal component of the plume when plume $\Delta T$'s were below the avoidance level of 11°C. Fish did not pass to the lower end of the raceway when plume $\Delta T$ exceeded 9-11°C. The responses noted in our experiments suggest organismic behavior may prevent juvenile salmon in nature from experiencing lethal conditions from thermal discharges and have application in waste heat management and utilization.

## INTRODUCTION

Behavioral responses of aquatic organisms to thermal discharges potentially mitigate or exacerbate ultimate exposure. Fish can detect temperature changes less than 0.1°C. [1-4] Some species of fish avoid high temperatures; [5-11] while others may be attracted to them. [12-17]

Previous workers in the Hanford reach of the Columbia River, southcentral Washington, drifted juvenile salmonids in cages through midriver thermal discharges from plutonium production reactors. [18] These fish survived while other fish died when drifted through warm water seepage areas near shore with less mixing and higher temperature differentials (ΔT's). However, the fate of unconfined juvenile salmon passing seward through the area could not be determined. Although some downstream migrants may have passed through the lower temperature midriver discharges, most were shoreline oriented [19] and were probably exposed to higher temperature seepage areas.

Our recent studies evaluated and documented the instaneous reactions of juvenile chinook salmon (Oncorhynchus tshawytscha) abruptly exposed to a simulated thermal discharge in a model raceway [20], at flows typical of shoreline areas. Although the Hanford production reactors have been shut down since 1971, the response of juvenile salmonids to thermal discharges is important in assessment of future power development in the Pacific Northwest and waste heat management.

## MATERIALS AND METHODS

The model raceway was 6 m long and 30x20 cm in cross-section. Since cross-sectional flow in a rectangular trough is not uniform, quarter-round sections of PVC pipe, 12.7 cm radius, were installed longitudinally in the lower corners to provide more uniform laminar flow. A white background provided contrast for observing and recording fish response. The raceway (Fig. 1) was supplied with untreated Columbia River water pumped through a head tank to aerate and reduce delivered water pressure. Water depth was maintained at 12 to 15 cm during testing by a weir at the raceway outlet. Current velocity was less than 0.6 m/s.

Heated water was discharged into the raceway through a slot in the bottom about 3 m downstream from the head tank to simulate a thermal discharge. Discharge temperatures were controlled and flow was a constant 0.25 l/s.

A canopy, 0.8 m above the raceway, provided a uniform overhead background, and prevented fish from seeing and reacting to observers. The canopy was fitted with fluorescent lighting to minimize shadow effects from sunlight. Two video cameras were positioned under the canopy, one up- and one downstream of the discharge. A third camera was located on top of the canopy directly above the discharge with its lens protruding through the canopy (Fig. 1).

Four series of tests, one with hatchery-reared and three with wild fish, were conducted at different ambient raceway temperatures (Table 1). Hatchery-reared juvenile chinook salmon (mean fork length, 5.0 cm) were used for initial testing in January 1976 (Series 1). Wild juvenile chinook salmon seined from the Columbia River, were tested in May (mean fork length, 4.1 cm, Series 2) and June (mean fork length, 4.4 and 6.6 cm, Series 3 and 4). Seined fish were transported in oxygenated containers to our Richland laboratories, and held 1 to 2 days in flow-through hatchery troughs at ambient river temperatures until testing. To initiate each test, 10 to 15 fish were transferred to a holding chamber about 2 m above the discharge in the upper raceway behind a retaining screen (Fig. 1). Raising the screen by remote control allowed fish to swim or drift with flow through the raceway. As fish entered the discharge area, their reactions were recorded on videotape (Sony ATV 1400 camera and VO 1800 recorder).[1] A closed circuit video-switcher and playback system was used for subsequent analyses.

Tests were conducted under three conditions: no discharge (control), ambient discharge (control on effects of current only) and heated discharge. The test matrix included up to six thermal variations which were monitored with sensitive thermister probes (YSI model 401) and quartz thermometers (HP Model 3801 A) attached to an analog converter (Model 580A/581A) with digital readout system. Probes were spaced in the raceway to measure ambient discharge and plume temperatures (Fig. 1). Discharge temperatures were transferred verbally from the digital readout to the videotapes and incremental temperatures ($\Delta T$'s) were calculated. Fish responses were subsequently evaluated from the videotapes during several playbacks.

Tests in each series (1-4) were categorized by thermal regime. The average temperature recorded by each thermistor probe was used to calculate the mean and range of plume temperatures during each test. Temperatures at any probe usually varied less than ±1°C. However, temperatures among probes varied up to 12°C because of their position relative to the point of discharge. The 12°C difference was rare and occurred only in January tests (Series 1). During May and June (Series 2-4) one probe was in the center of the discharge orifice below the

---

[1] Mention of trade names does not imply endorsement by Battelle

raceway bottom and subject to the maximum incremental temperature. Mixing of the plume accounted for lower temperatures at other probes depending on probe position. Temperatures at the discharge probe were not included in calculating the mean and range of plume temperatures.

## RESULTS AND DISCUSSION

Our work corresponded in time with the natural downstream migration of juvenile chinook salmon from the central Columbia River [19, 21] and employed river water at ambient temperatures. Thus, seasonal timing, fish age and development, and regional climatic and water conditions for downstream migration were approximated in the raceway.

Videotape analysis revealed five response categories: Fish (1) passed through the discharge with no apparent reaction; (2) temporarily held position in the plume downstream of the discharge orifice; (3) darted or increased speed; (4) twitched or exhibited spasms while passing the discharge orifice; or (5) avoided the discharge by darting upstream after encounter. Category 5 includes some tests in which fish voluntarily held position in the plume for several minutes before darting upstream (Table 1).

With no discharge plume, fish drifted or swam to the downstream end of the raceway and then moved up and down along its length. At ambient or low plume temperatures, fish held briefly in the plume but still swam the length of the raceway. When the ΔT of the discharge plume exceeded 9-11°C, fish did not go to the downstream end of the raceway. The higher the average ΔT, the more rapidly fish avoided the discharge by moving upstream. Juvenile chinook salmon clearly avoided temperature increases stressful to coldwater fish [22]. Negative pseudo-rheotaxis [23] at higher temperatures [24] was not observed.

Each separate test utilized naive fish. However, fish in each test were allowed several exposures to their particular thermal regime. After repeated trials at higher plume temperatures, fish would not move downstream or approach the discharge. This indicated that avoidance conditioning occurred in that group of test fish.

Although acute (short-term) preferred temperatures of some fish species increase with acclimation temperature [25], those of others [5], including juvenile spring chinook salmon [3], are only slightly affected or decrease [26]. Our studies show that the mean plume temperature which causes avoidance by young fall chinook salmon increases with acclimation temperature. However, the mean $\Delta T$ avoidance remained relatively constant at 9-11°C. In test series 3, conducted at 13°C ambient temperatures, some avoidance was observed at a mean $\Delta T$ of 4 but not at a $\Delta T$ of 6°C. However, fish that exhibited avoidance appeared to move along the raceway bottom, directly over the discharge orifice, and intersect the maximum discharge temperature (25°C). This also occurred with tests in which discharge orifice temperatures ranged from 25-37°C, and spasmodic responses were observed. Temperatures causing spasmodic contractions of somatic muscles were generally above the 25.1°C ultimate upper incipient lethal level [3] for the species.

We found no evidence of thermal attraction. Fish all behaved alike, and displayed positive pseudo-rheotaxis and maintained position in the discharge current at ambient and low discharge temperatures. This suggest juvenile chinook salmon that encounter low ($\Delta T$ <9°c) temperature discharges in nature may orient or remain in low-velocity (<0.6 m/s) discharge currents. Studies in Lake Michigan [27] suggest adult salmonids are extremely mobile but may spend some time in the area of nuclear power plant discharges. If discharges also contain chemical additives such as chlorine, mortalities may result from combined effects [28, 29]. Several studies indicate fish will avoid various chemical changes in water [30-40]. However, menhaden attracted to thermal discharges have experienced mass mortalities from gas bubble disease [16], and copper [41], DDT [42], toxaphene [43] and other pesticides [44] and other chemicals may alter fish responses to temperature. Salinity [8, 9] light [3, 9, 45, 46] bacterial pyrogens [47] other environmental variables, feeding activity [3, 10, 45] and social behavior [45, 48] also affect fish responses to temperatures.

The assessment of environmental effects of thermal discharges on aquatic systems involves several phases. The ecologist must determine what environmental factors are, or will be altered, the degree of alteration, and the kinds of organisms present. He must be cognizant of the sensitivity or tolerance and reactions of the organisms exposed to the discharge, to predict potential effects at the population level. Most often, however, predictions are based on bioassay tolerance data on effects of various thermal increments and chemical concentrations above ambient and unsubstantiated assumptions of organism exposure. The missing link is the paucity of information on behavior of mobile organisms in their natural environment.

Nuclear power plants that discharge water at ambient temperatures or slightly above may not protect certain fish species if other effluent components act in combination to cause mortalities or alter avoidance responses. Discharge of hotter or higher velocity effluents may be necessary in certain cases to cause avoidance of lethal conditions. The responses noted in our experiments suggest organismic behavior may prevent juvenile chinook salmon in nature from experiencing lethal conditions from thermal discharges. However, the interaction of various environmental stimuli and their influence on fish response need elucidation. Clearly, knowledge of the behavioral responses of aquatic organisms to heat and chemicals 1) puts bioassay tolerance studies in perspective, 2) is essential for proper design and operation of thermal outfall structures, and 3) is an important consideration in waste heat management and utilization.

## ACKNOWLEDGMENT

We thank Dr. C. D. Becker who critically reviewed the manuscript. Drs. T. J. Connors, E. Hunt, M. J. Schneider, and J. Vaughn contributed to raceway design and development. The study was supported by the U.S. Energy Research and Development Administration under contract EY-76-C-06-1830 with Battelle Memorial Institute, Pacific Northwest Laboratories.

## LITERATURE CITED

1. Bull, H.D. 1936. Studies on conditioned responses in fishes VII. Temperature preception in teleosts. J. Mar. Biol. Assoc. U.K. 21:1-27.

2. Dijkgraaf, S. 1940. Untersuchungen über den temperatursinn der fische. Z. Vgl. Physiol. 27:587-605.

3. Brett, J.R. 1952. Temperature tolerance in young Pacific salmon genus Oncorhynchus. J. Fish Res. Board Can. 9:265-323.

4. Bardach, J.E., and R. G. Bjorkland. 1957. The temperature sensitivity of some American freshwater fishes. Am. Nat. 41:233-251.

5. Doudoroff, D. 1938. Reactions of marine fishes to temperature gradients. Biol. Bull. Woods Hole, Mass. 75:494-509.

6. Alabaster, J.S. 1963. The effect of heated effluents on fish. Int. J. Air Water Pollut. 7:541-563.

7. Moss, S.A. 1970. The responses of young American shad to rapid temperature changes. Trans. Am. Fish Soc. 99:381-384.

8. Meldrim, J.W. 1971. An experimental study of the behavior of estuarine fishes to a proposed thermal effluent. Pages 65-74 in G. P. Rasmussen ed. Proceedings of the 4th Mid-Atlantic Industrial Waste Conference Univ. of Del. Newark, DE 434 pp.

9. Meldrim, J.W. and J.J. Gift. 1971 Temperature preference avoidance and shock experiments with estuarine fishes. Ichthyological Associates, Bull. 7. Middletown, DE 77 pp.

10. Neill, W.H. and J.J. Magnuson 1974. Distributional ecology and behavioral thermoregulation of fishes in relation to heated effluent from a power plant at Lake Monona, Wisconsin. Trans. Am. Fish. Soc. 103:663-710.

11. Cherry, D.S., R.K.Guthrie, J.H. Rodgers, Jr., J. Cairns, and K.L. Dickson. 1976. Responses of mosquitofish (Gambusia affinis) to ash effluent and thermal stress. Trans. Am. Fish Soc. 1976 (6):686-694.

12. Hancock, H.M. 1954. Investigations and experimentation relative to winter aggregations of fishes in Canton Reservoir, Oklahoma. Okla. Agric. Mech. Coll., Res. Found. Pub. No. 58, 104 pp.

13. Graham, J.J. 1956. Observations of the alewife *Mollobos pseudoharengus* (Wilson) in freshwater. Univ. Tronto Stud. Biol. Ser., No. 62. 43 pp.

14. Young, J.S. and C.I. Gibson. 1973. Effect of thermal effluent on migrating menhaden. Mar. Pollut. Bull. 4:94-96.

15. Young, J.S. 1974. Menhaden and power plants - a growing concern. Mar. Fish Rev. 36:19-23.

16. Marcello, R.A., Jr., and R.B. Fairbanks. 1974. Gas bubble disease mortality of Atlantic menhaden (*Brevoortia tyrannus*) at a costal power plant. Pages 75-80 in D.H. Fickeisen and M.J. Schneider,(eds) Gas Bubble Disease. USERDA CONF-741033 Richland, WA 124 pp.

17. Beitinger, T.L. and J.J. Magnuson. 1976. Low thermal responsiveness in the bluegill, *Lepomis macrochirus*. J. Fish. Res. Board Can. 33:293-295.

18. Becker, C.D., C.C. Coutant, and E.F. Prentice. 1971. Ecological evaluation of migration of juvenile chinook salmon in relation to heated effluents in the central Columbia River. Pages 528-536 *in* Proc. Third National Symposium on Radioecology. USAEC, Conf-710501-P1. Oak Ridge, Tenn.

19. Mains, E.M., and J.M. Smith. 1964. The distribution, size, time and current preferences of seaward migrant chinook salmon in the Columbia and Snake Rivers. Washington Dep. Fish. Fish. Res. Pap. 2:5-43.

20. Gray, R.H., with R.G. Genoway and S.A. Barraclough. 1977. Behavior of juvenile chinook salmon (*Oncorhynchus tshawytscha*) in relation to simulated thermal effluent. Trans. Am. Fish. Soc. (in press).

21. Becker, C.D. 1970. Temperature, timing and seaward migration of juvenile chinook salmon from the central Columbia River. USAEC R&D Report. BNWL-1472. Battelle Pacific Northwest Labs., Richland, WA 21 pp.

22. Sylvester, J.R. 1972. Possible effects of thermal effluents on fish: A review. Environ. Pollut. 3:205-215.

23. Gray, J. 1937. Pseudo-rheotropism in fishes. J. Exp. Biol. 14:95-103.

24. Keenlyside, M.H., and W.S. Hoar. 1954. Effects of temperature on the responses of young salmon to water currents. Behaviour 7:77-87.

25. Fry, F.E.J. 1947. Effects of the environment on animal activity. Univ. Toronto Biol. Ser. 55:1-62.

26. Garside, E.T., and J.S. Tait. 1958. Preferred temperature of rainbow trout (*Salmo gairdneri Richardson*) and its unusual relationship to acclimation temperature. Can. J. Zool. 36:563-567.

27. Spigarelli, S.A. 1975. Behavioral responses of Lake Michigan fishes to a nuclear power plant discharge. Pages 479-498 *in* Environmental effects of cooling systems nuclear power plants. IAEA-SM-187/18, Vienna, Austria.

28. Stober, Q.J., and C.H. Hanson. 1974. Toxicity of chlorine and heat to pink (*Oncorhynchus gorbuscha*) and chinook salmon (*O. tshawytscha*) Trans. Am. Fish. Soc. 103:569-576.

29. Thatcher, T.O., M.J. Schneider, and E.G. Wolf. 1976. Bioassays on the combined effects of chlorine, heavy metals and temperature on fishes and fish food organisms. Part I. Effects of chlorine and temperature on juvenile brook trout (*Salvelinus fontinalis*). Bull. Environ. Contam. Toxicol. 15:40-48.

30. Shelford, V.E., and W.C. Allee. 1913. The reactions of fishes to gradients of dissolved atmospheric gases. J. Exp. Zool. 14:207-266.

31. Jones, J.R.E. 1952. The reactions of fish to water of low oxygen concentrations. J. Exp. Biol. 29:403-415.

32. Smith, W.E., and R.W. Saalfeld. 1955. Studies on Columbia River smelt Thaleichthys pacificus (Richardson) Washington Dep. Fish. Fish. Res. Pap. 1:3.

33. Jones, B.F., C.E. Warren, C.E. Bond, and P. Doudoroff. 1956. Avoidance reactions of salmonid fishes to pulp-mill effluents. Sewage and Ind. Wastes. 28 (11): 1403-1413.

34. Whitmore, C.M., C.E. Warren, and P. Doudoroff. 1960. Avoidance reactions of salmonid and centrarchid fishes to low oxygen concentrations. Trans. Am. Fish. Soc. 89:17-26.

35. Sprague, J.B. 1965. Avoidance of copper-zinc solutions by young salmon in the laboratory. J. Water Pollut. Control Fed. 36:990-1104.

36. Sprague, J.B. 1968. Avoidance reactions of rainbow trout to zinc sulphate solutions. Water Res. 2:267-372.

37. Sprague, J.B., P.F. Elson and R.L. Saunders. 1965. Sub-lethal copper-zinc pollution in a salmon river - a field and laboratory study. Inter. Air Water Pollut. 9:531-543.

38. Sprague, J.B., and D.E. Drury. 1969. Avoidance reactions of salmonid fish to representative pollutants. pages 169-179. in Advances in Water Pollution Research. Pergamon Press, New York, N.Y.

39. Lawrence, M., and E. Scherer. 1974. Behavioral responses of whitefish and rainbow trout to drilling fluids. Tech. Rep. No. 502 Res. Dev. Dir. Freshwater Inst. Winnipeg, Manitoba, 47 pp.

40. Fava, J.A., and C. Tsai. 1976. Immediate behavioral reactions of blacknose dace. Rhinichtys atraculus, to domestic sewage and its toxic constituents Trans. Am. Fish. Soc. 106:430-441.

41. Kleerekoper, H., J.G. Waxman, and J. Matis. 1973. Interaction of temperature and copper ions as orienting stimuli in the locomotor behavior of the goldfish (*Carassius auratus*). J. Fish Res. Board Can. 30:725-728.

42. Ogilvie, D.M., and J.M. Anderson. 1965. Effect of DDT on temperature selection by young Atlantic salmon, *Salmo salar*. J. Fish Res. Board Can. 22:503-512.

43. Ludwig, H.F. 1965. Toxicant-induced behavioral and histological pathology. A quantitative study of sublethal toxication in the aquatic environment. Final Report 1962-63 for Division Water Supply and Pollution Control. U.S. Public Health Service Engineering Science Inc. Oakland, CA 123 pp.

44. Warner, R.E., K.K. Peterson, and L. Borgmann. 1966. Behavioral pathology in fish: A quantitative study of sublethal pesticide toxication. J. Appl. Ecol. 3:223-247.

45. Pearson, B.E. 1952. The behavior of a sample of hybrid trout (*Salvelinus fontinalis* x *Cristivomer namaycush*) in a vertical temperature gradient. Ontario Fish Research Lab., Toronto, 24 pp.

46. Sullivan, C.M., and K.C. Fisher, 1954. The effects of light on temperature selection in speckled trout, *Salvelinus fontinalis* (Mitchill). Biol. Bull. Woods Hole, Mass. 107:278-288.

47. Reynolds, W.W., M.E. Casterlin and J.B. Covert. 1976. Behavioral fever in teleost fishes. Nature 259:41-42.

48. Beitinger, T.L., and J.J. Magnuson. 1975. Influence of social rank and size on the thermoselection behavior of bluegill (*Lepomis macrochirus*) J. Fish Res. Board Can. 32:2133-2136.

## TABLE 1. AVOIDANCE OF THERMAL EFFLUENT BY JUVENILE CHINOOK SALMON (ONCHORHYNCHUS TSHAWYTSCHA)

| WATER TEMPERATURE (°C) | | | | | | |
|---|---|---|---|---|---|---|
| | | Plume | | | | |
| Ambient | Point of Discharge | Mean | Range | Mean ΔT | Number of Tests(a) | % OF FISH EXHIBITING AVOIDANCE |
| | | **Series 1 - Hatcher Fish** | | | | |
| 5 | - | 11 | 10-13 | 6 | 1 | 0 |
| 6 | - | 14 | 10-17 | 8 | 2 | 0 |
| 5 | - | 16 | 12-20 | 11 | 4 | 78 (b) |
| 6 | - | 19 | 12-24 | 13 | 5 | 88 |
| 5 | - | 21 | 15-25 | 16 | 1 | 100 |
| | | **Series 2 - Wild Fish** | | | | |
| 12 | - | (No Plume) | | - | 2 | 0 |
| 12 | 12 | (Ambient Plume) | | | 2 | 0 |
| 12 | 23 | 16 | 14-16 | 4 | 1 | 0 |
| 12 | 29 | 17 | 15-19 | 5 | 3 | 0 |
| 12 | 29 | 18 | 16-21 | 6 | 10 | 0 |
| 12 | 27 | 22 | 20-23 | 10 | 1 | 100 (b) |
| 12 | 35 | 24 | 24-25 | 12 | 2 | 100 |
| 12 | 37 | 26 | 25-27 | 14 | 1 | 100 |
| | | **Series 3 - Wild Fish** | | | | |
| 13 | - | (No Plume) | | - | 2 | 0 |
| 13 | 13 | (Ambient Plume) | | | 2 | 0 |
| 12 | 16 | 13 | 13-16 | 1 | 1 | 0 |
| 13 | 23 | 15 | 13-18 | 2 | 2 | 0 |
| 13 | 27 | 16 | 13-20 | 3 | 2 | 0 |
| 13 | 25 | 17 | 14-21 | 4 | 2 | 75 (b) |
| 13 | 26 | 19 | 16-22 | 6 | 2 | 0 |

## TABLE 1. (CONTINUED)

Series 4 - Wild Fish

| | | | | | | |
|---|---|---|---|---|---|---|
| 15 | - | (No Plume) | | - | 2 | 0 |
| 15 | 15 | (Ambient Plume) | | | 1 | 0 |
| 16 | 23 | 21 | 19-21 | 5 | 2 | 0 |
| 15 | 28 | 23 | 23-25 | 8 | 2 | 0 |
| 16 | 31 | 25 | 24-26 | 9 | 2 | 100 |
| 16 | 34 | 27 | 26-28 | 11 | 2 | 100 |

---

[a] 10-15 fish per test

[b] response was not instantaneous but occurred within 5-10 min.

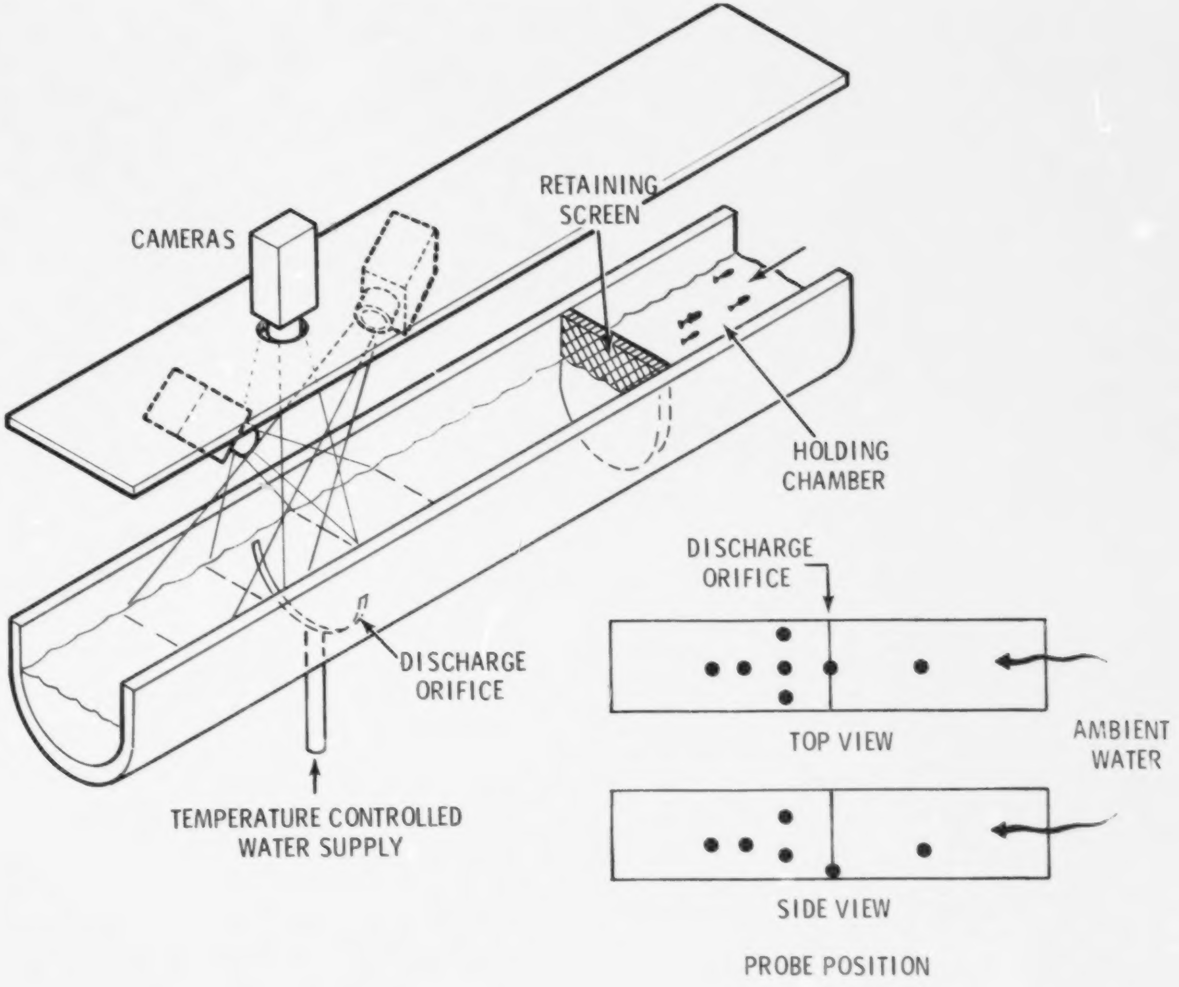

RETAINING
SCREEN
CAMERAS
HOLDING
CHAMBER
DISCHARGE
ORIFICE
DISCHARGE
ORIFICE
TEMPERATURE CONTROLLED
WATER SUPPLY
TOP VIEW
AMBIENT
WATER
SIDE VIEW
PROBE POSITION

Figure 1. Schematic of raceway showing overhead canopy, video cameras, discharge orifice, retaining screen, holding chamber (upper left) and position of temperature probes (lower right). Head tank, and flourescent lights, not shown (from Gray et.al. 1977).

15-45-25

III-B-87

# THE BIOLOGICAL IMPACT OF A THERMAL DISCHARGE EXCEEDING $95^{\circ}$F - A CASE STUDY OF ALLEN STEAM STATION, NORTH CAROLINA

D. W. Anderson and A. Gnilka
Duke Power Company
Charlotte, North Carolina U.S.A.

## ABSTRACT

North Carolina and South Carolina water quality standards limit thermal discharges to a $90^{\circ}$F maximum with $\Delta T$ rises above background of $5^{\circ}$F for North Carolina and $3^{\circ}$F for South Carolina. These standards were legislated in early 1970 to insure the protection and propagation of aquatic biota in these two states.

Duke Power Company's 1155 MWe Allen Steam Station, located in North Carolina on Lake Wylie, utilizes the lake waters for once-through condenser cooling. This station began its initial operation in 1957. During the summer months the discharge is heated to a monthly average maximum above $101^{\circ}$F, with instantaneous values in excess of $106^{\circ}$F. In 1973, Duke Power Company conducted several detailed scientific studies of the lake both to verify the station's 20-year historical record of "no adverse environmental impact" and to determine why its thermal effluent was not showing the impact on aquatic life that might be expected based on discharge temperatures above standards.

The major conclusion of the studies was that Allen Steam Station's cooling water discharge had no overall adverse effect on the ecology of Lake Wylie. Measurable physical, chemical and biological effects associated with the thermal effluent were confined to a small area in the immediate vicinity of the discharge, and were difficult to separate quantitatively from natural background variations. Results of the studies comprised the scientific basis which allowed the station to obtain modified thermal discharge limitations above "standards" limits via a successful 316(a) Demonstration.

The practical perspective gained as a result of the Allen Steam Station studies shows that legislated thermal effluent criteria and standards should not be taken as absolute limits beyond which environmental damage will result. At best, they should serve only as general guidelines whenever sound scientific data and actual operating experience are not available as a basis for setting realistic thermal standards. Hopefully, as existing water quality standards are reviewed and revised, recognition of scientific field study results, such as those developed at the Allen Steam Station, will enable regulatory authorities to establish realistic standards to the overall benefit of both the environment and the public.

## INTRODUCTION

The evolution of present-day thermal standards for fresh waters can be traced to the recommendations of the National Technical Advisory Committee (NTA) (the "Green Book") [1] concerning temperature criteria for warm water fishes; specifically, "during any month of the year, heat should not be added to a stream in excess of the amount that will raise the temperature (at the expected minimum daily flow for that month) more than 5°F." It was further recommended that in the epilimnion of lakes and reservoirs a 3°F ΔT should be the maximum allowed temperature based on a monthly average of maximum daily temperature. Using hypolimnetic waters for thermal station condensers was also discouraged.

The committee made temperature recommendations for selected warm and cold water fishes and presented them in combination in one table. This table also included some temperature-related life history information such as a 48°F requirement for spawning and egg development of lake trout, walleye, northern pike, sauger and Atlantic salmon, and a 93°F temperature limit for growth of catfish, gar, white or yellow bass, spotted bass, buffalo, carpsucker, threadfin shad and gizzard shad. This table was entitled "Provisional maximum temperatures recommended as compatible with the well-being of various species of fish and their associated biota."

The "Green Book" temperature recommendations formed the basis for State Water Quality Standards the bulk of which were approved by 1971. Most states "adopted" the "Green Book" temperature recommendations without, apparently, considering the NTA's admonition "in view of the many variables, it seems obvious that no single temperature requirement can be applied to the United States as a whole, or even to one State; the requirements must be closely related to each body of water and its population." Thus, the general and provisional temperature recommendations of the "Green Book," in effect, became the law of the land with no regard given to the NTA's admonition.

In 1971, EPA requested that the National Academy of Sciences and the National Academy of Engineering (NAS-NAE) undertake a revision of the "Green Book," the so-called "Blue Book" [2]. The "Blue Book" placed the thermal standards into an ecological perspective by including the concept of a mixing zone and the capacity of fish to avoid areas of unfavorable temperatures. However, before the "Blue Book" was published EPA began its own revision of the "Green Book" (called the "Red Book" [3]) which would also supersede the "Blue Book." The thermal recommendations of the "Red and Blue Books" are generally similar except in one important aspect — the EPA version (the "Red Book") makes no reference to a mixing zone.

The overall result of all the scientific input into the "Green, Blue and Red Books" as a basis for promulgating thermal standards was that the "provisional" temperatures used in the "Green Book" were, and still are, the cornerstone of the majority of state thermal standards. EPA did recognize the importance of site specificity for thermal standards and provided a mechanism for exemptions from standards via 316(a) Demonstrations which "will assure the protection and propagation of a balanced indigenous population of shellfish, fish and wildlife" [4]. The following discussion of the biological impact of a thermal discharge exceeding 95°F is largely based on Duke Power Company's successful 316(a) Demonstration for Plant Allen [5].

## LEGAL BACKGROUND - PLANT ALLEN

Under the 1972 Amendments to the Federal Water Pollution Control Act (the Act) operators of steam electric power generating units must comply with applicable technology based effluent limitations promulgated by the Administrator of Environmental Protection Agency. These Limitations, Effluent Guidelines and Standards are published at 40 C.F.R. Part 423. In addition, compliance with effluent limitations calculated to achieve water quality standards is required under Section 301(b) (1) (C) of the Act. With respect to the discharge of heat, however, an exemption from any of these limitations is available if the operator can make a successful demonstration under Section 316(a) of the Act.

There are five fossil-fired electric generating units in operation at Plant Allen, all of which were placed in commercial operation prior to January 1, 1970. They are thus "old" units as defined in the Effluent Guidelines and Standards and exempt from the "no discharge of heat" limitations. Thus, the Effluent Guidelines and Standards impose no restrictions on discharge of heat from Allen Units 1-5.

According to water quality standards for the State of North Carolina, however, the temperature of receiving waters cannot exceed 90°F (32.2°C) and cannot exceed 5°F (2.8°C) above natural temperatures beyond the boundary of an assigned mixing zone. Under the State of South Carolina water quality standards, the temperature of receiving waters cannot exceed 90°F (32.2°C) and cannot exceed 3°F (1.7°C) above natural temperatures beyond the boundary of an assigned mixing zone. A mixing zone for Plant Allen had been assigned by the State of North Carolina; however, due to the nature of the flow pattern of the heated water discharge, the thermal plume from Plant Allen could not be so confined. Unless Duke could successfully demonstrate via 316(a), it would be necessary to backfit cooling towers to Plant Allen at a cost of over $30,000,000. Accordingly, Duke Power Company has requested that alternative, less stringent thermal effluent limitations be imposed under Section 316(a) for the heated water discharge from all units at Plant Allen.

## DESCRIPTION OF PLANT ALLEN AND LAKE WYLIE

Plant Allen, located on Lake Wylie, has five independent generating units which have a combined nameplate capacity of 1155 MWe (Figures 1 and 2). Units 1 and 2, which began commercial operation in 1957, are each rated at 165 MWe. Units 3, 4, and 5, each rated at 275 MWe, became operational in 1959, 1960 and 1961, respectively. Condenser cooling water for Plant Allen (maximum design flow 1334 cfs or 37.8 $m^3$/s) is drawn from the Catawba River Arm of Lake Wylie and discharged through a 3/4 mile long discharge canal into the South Fork Catawba River Arm (Figure 2). The winter and summer condenser cooling water design flows and temperature rises for Plant Allen are summarized as follows:

| | Winter | Summer |
|---|---|---|
| Condenser Cooling Water Flow, cfs ($m^3$/s) | 803 (22.7) | 1334 (37.8) |
| Temperature Rise $\Delta T$, °F (°C) | 29 (16.1) | 18 (10.0) |

Presented in Table 1 are recent monthly average intake temperatures, discharge temperatures and plant $\Delta T$'s for the period 1968-1974. A comparison of Table 1 data with the design values indicates that during the winter months, plant $\Delta T$'s were well below the design value of 29°F (16.1°C) with the highest monthly average $\Delta T$ being 25.8°F (14.3°C). During the traditional summer months of June, July and August, the greatest plant $\Delta T$ was 18.9°F (10.5°C). The highest monthly average discharge temperature tabulated is 101.6°F (38.7°C). Historical monthly average intake temperatures are also presented in Reference 6.

Lake Wylie was created in 1904 with the construction of a dam on the Catawba River for hydroelectric power production. The original impoundment acreage was increased in 1925 when the dam was raised 50 feet (15.2 m) and a new 60 MWe hydroelectric facility was constructed. Lake Wylie, which is located in both North and South Carolina, extends north from Wylie Dam up the Catawba River 28 miles (45 km) and extends approximately five miles (8.0 km) up the South Fork of the Catawba River.

At full pond elevation 569.4 (174 m) msl, Lake Wylie has a surface area of 12,455 acres (50 $km^2$), a shoreline of about 325 miles (523 km), a volume of 281,900 ac-ft ($3.46 \times 10^8 m^3$), and a mean depth of 22.5 ft (6.9 m). Its total watershed is approximately 3020 $mi^2$ (7818 $km^2$), which yields an average flow of 4100 cfs (116 $m^3$/s) through Wylie Dam resulting in a 32-day theoretical retention time. An area-volume curve for Lake Wylie is presented in Figure 3.

Lake Wylie is characterized by winter water temperatures exceeding 39°F (4°C), by thermal stratification during the summer, and by complete mixing during the winter, typical of a monomictic lake. Lake Wylie usually reaches its coolest temperature of about 44°F (7°C) by mid-January. By late March the lake begins to exhibit natural thermal stratification which becomes well established by the end of April and is maintained throughout the summer. The fall overturn usually occurs in September and the lake becomes completely mixed. The intensity of stratification and the occurrence of overturn are influenced by the operation of Wylie and Mountain Island Hydroelectric Stations operation. Thermal stratification is usually characterized by temperature differences from surface to bottom of not more than 9-11°F (5-6°C), and overturn may occur as early as August. This early overturn is due to the low level withdrawals by the hydroelectric station.

## THERMAL CONSIDERATIONS

Based on the modified MIT model [7] the simulated monthly average thermal plume acreages, shorelines in the elevated temperature region, and their respective percentages of the total lake values for the extreme summer and winter conditions are presented in Table 2 and Figures 4 and 5. The thermal plume is herein defined as 90°F (32°C) or 3°F (1.7°C) $\Delta T$ excess above background lake temperatures in South Carolina, and as 90°F (32°C) or 5°F (2.8°C) $\Delta T$ in North Carolina. Under extreme winter conditions 2800 ac (11.3 $km^2$) representing 22% of the surface area of Lake Wylie was simulated to be 3°F (1.7°C) above ambient lake temperatures, as a result of Plant Allen. This drops to 1950 ac (7.9 $km^2$) or 16% of the lake surface when a 5°F (2.8°C) $\Delta T$ is considered.

## ENVIRONMENTAL MONITORING - RESULTS AND DISCUSSION

### Water Quality

A study of Lake Wylie water quality was conducted from September 1973 to August 1974 [6] (see Figure 6 for sampling locations). Weekly profiles of temperature, oxygen, conductivity, pH and transmissivity and monthly chemical and bacteriological analyses were made at 20 locations throughout the lake during the year. These studies indicated that the study area was comprised of three distinct water systems: the Catawba River Arm, typical of a well-mixed river; the South Fork Catawba River Arm, an artificially stratified system resulting from the flow of ambient South Fork water beneath the Plant Allen thermal effluent; and the Main Body of Lake Wylie.

Concentrations of major chemical constituents were typical of a drainage system originating in an area underlain by igneous and metamorphic bedrock. The highest values of most parameters occurred in ambient South Fork Arm waters, unaffected by the Allen discharge. These values probably reflected the upstream discharges of industrial and municipal wastes [6].

Associated with industrial and municipal waste discharges are decreased oxygen concentrations ("oxygen sags") some distance below the point of discharge. These oxygen sags, if they develop, can be accentuated by increased temperatures due to thermal effluents. An analysis of theoretical considerations and existing data [6] revealed that the Plant Allen thermal discharge has little or no measurable effect on the oxygen concentration (organic loading) of the South Fork Arm of Lake Wylie.

Catawba River waters had a predominant effect on water quality within the main body of Lake Wylie. However, chemical and bacteriological parameters characteristic of ambient South Fork water were sometimes measured in Lake Wylie bottom water as far as 10 miles downstream from the confluence of the

South Fork and Catawba Rivers [6]. Overall, the Plant Allen discharge exerted a positive effect on the chemical and bacteriological quality of the South Fork Catawba River Arm waters by diverting higher quality Catawba River Arm waters into the comparatively lower quality South Fork water.

## Phytoplankton Community

The phytoplankton community of the Catawba River Arm of Lake Wylie in the vicinity of Plant Allen was studied from February 1973 to January 1974 [8] and from September 1973 to August 1974 by Industrial Bio-Test Laboratories [6] (see Figure 6 for sampling locations). Monthly quantitative phytoplankton samples were taken by both researchers in Lake Wylie including the Catawba River Arm and the South Fork Catawba River Arm.

The upstream impoundments of the Catawba River System were probably the origin of the majority of phytoplankton species in the Catawba River Arm and in Lake Wylie [6]. The South Fork did contribute a small but distinctive riverine type flora [6]. Results of seasonal phytoplankton population studies indicated that lowest densities of all algal divisions occurred in winter. Maximum densities varied seasonally for each algal division. The diatoms (Bacillariophyta) and the green algae (Chlorophyta) dominated the phytoplankton in Lake Wylie. Diatoms reached their greatest abundance in May and the principal genera included *Melosira*, *Stephanodiscus* and *Cyclotella*. Maximum densities for the green algae occurred in June. The most abundant green algal taxa were *Chlamydomonas*, *Nannochloris*, *Mesostigma* and *Scenedesmus* [6].

The blue-green algae (Cyanophyta) were a minor constituent of the total phytoplankton populations. The most quantitatively important blue-green algal taxa were the colonial genera *Aphanocapsa*, *Aphanothece*, *Merismopedia* and *Microcystis* and the filamentous *Anabaena* and *Oscillatoria*.

The dinoflagellates (Pyrrhophyta), yellow-brown algae (Chrysophyta), euglenoids (Euglenophyta), cryptomonads (Cryptophyta) and the chloromonads (Chloromonadophyta) were present in relatively low numbers and accounted for a negligible portion of biomass compared to the diatoms and green algae [6].

Thermal discharges from Plant Allen into the South Fork Catawba River Arm spread uplake as well as downlake and diluted the nutrient-rich waters of the South Fork [8]. The South Fork Catawba River Arm contained a small but distinctive phytoplankton community consisting mainly of pennate diatoms, non-motile green algae and euglenoids [6]. The operation of Plant Allen caused a thermal stratification in the discharge area and a subsequent phytoplankton stratification. Phytoplankton taxa characteristic of the Catawba River Arm were more prevalent in the heated surface water while phytoplankton taxa typical of South Fork Catawba River Arm were more frequently found in the cooler, deeper water. At the interface of the plume and ambient South Fork waters, a highly variable degree of mixing between the two phytoplankton assemblages was observed [6]. There was no evidence that the thermal discharge from Plant Allen had been or is causing any shift in the phytoplankton flora of South Fork Arm to more heat-tolerant species [8].

Bioassay results indicated that the Lake Wylie study area waters were not conducive to the overabundant growth of potential nuisance blue-green algae [6]. Furthermore, these results did not indicate any influence of Plant Allen on the ability of the Lake Wylie study area waters to support algal growth as a function of nutrient content [6]. It is concluded that the operation of Plant Allen had no influence on the quantitative and/or qualitative variation of plankton below the confluence of the Catawba River Arm and South Fork Catawba River Arm.

### Zooplankton Community

The zooplankton community of Lake Wylie in the vicinity of Plant Allen was sampled monthly from February 1973 to January 1974 by Weiss *et al*. [8], and monthly from September 1973 to August 1974 by Industrial Bio-Test [6] (see Figure 6 for sampling locations).

The rotifers were the most numerically abundant constituents of the Lake Wylie zooplankton community [6] [8]. The rotifer population densities were generally greater during April through August with highest populations occurring in April and May. Dominant rotifers, those genera comprising 10% or more of the total zooplankton, included *Asplanchna*, *Brachionus*, *Conochiloides*, *Conochilus*. *Keratella*, *Polyarthra* and *Synchaeta*. *Keratella* and *Polyarthra*, the most common genera, were present throughout the year and attained greatest population densities in May. *Brachionus* was a summer form and was dominant only in the South Fork. *Conochiloides* and *Conochilus* were dominant summer forms. *Asplanchna* was the dominant genus only in the spring. *Synchaeta* was the only genus present throughout the year which had two density maxima: one in January and one in May.

The most abundant cladocerans were *Bosmina* and *Daphnia* [6] [8]. The various cladoceran genera exhibited seasonal differences in abundance, but they comprised only an average of 10% of the total zooplankton population [6]. *Bosmina* was present all year long and exhibited population pulses in spring and fall [6]. *Daphnia* was common in February and attained maximum abundance in May. The greatest adult copepod population densities were present during the fall and spring. The rotifer, cladoceran and copepod populations exhibited fluctuations in densities typical of reservoirs and lakes of the Piedmont region [8].

Operation of Plant Allen did not cause a reduction in the species diversity of zooplankton. The discharge of condenser cooling water from Plant Allen had no measurable overall influence on zooplankton populations in Lake Wylie [6].

### Benthic Macroinvertebrates

A quantitative survey of the benthos of Lake Wylie was conducted from October 1973 through August 1974 [6] and 1972 [9]. Samples were taken every two months from October to April, and every month thereafter through the spring and summer [6] (see Figure 6 for sampling locations).

A total of 121 taxa were reported in benthos collected from Lake Wylie during the 1973-74 studies [6]. Total numerical densities averaged approximately 1500 organisms per $m^2$ throughout the study area. No consistent pattern of change with season was apparent at any station; differences which did occur were associated with changes in sediment type.

Benthic biomass was dominated by the Asiatic clam (*Corbicula manilensis*) which first appeared in Lake Wylie about 1968 [6]. With the exception of those from the South Fork Arm of the lake, most (sometimes 99%) of the *Corbicula* were immatures. Although the density of the immatures fluctuated widely with location and time, that of the adults remained relatively constant throughout the study.

Approximately 30% by number of the benthos in Lake Wylie are insect larvae of the family Chironomidae. The 40 taxa represented also made it the most diverse group collected. Chironomids were most common in fine-grained sediment in shallow water, less so in rocky areas and, in deeper water, they tended to be replaced by larvae of *Chaoborus punctipennis*.

Equally abundant and almost as diverse as the Chironomids were the oligochaetes, which comprised 50% by number of the total benthos collected during the study [6]. They varied markedly, however, in both density and species composition among stations and with time.

Numerous other taxa of macroinvertebrates were collected. These included the larvae of a variety of insect groups (mayflies, dragonflies, caddisflies and beetles, among others), molluscs, leeches, a freshwater spong and a variety of minor invertebrate groups. They did not constitute more than 10% by number of the total benthos for the study period. All species found are common to freshwater lakes and rivers.

Only two areas sampled for benthos exhibited an influence of the Allen thermal discharge. One, in the shallow areas near shore at the mouth of the discharge cove, averaging 5.8°C (10.4°F) higher than the intake temperature; the other, in the shallow areas near shore one mile downlake of the discharge, averaging 5.6°C (10.1°F) higher than the intake. In one study the effects of the thermal discharge on the benthos revealed that the number of organisms whose population density increased was approximately equal to the number of organisms whose population decreased [9]. In this study it was also reported that in the discharge area "overall productivity was depressed, but this effect was limited to the discharge canal and the immediate area of discharge into the lake" [9]. In a more recent study [6] the diversity index, a relative measure of environmental stress, was consistently lower in the Allen discharge area than in other areas of Lake Wylie. However, the overall conclusions of the report are that "the thermal discharge from the Allen Station did not have an overall influence on benthic macroinvertebrates in the Lake Wylie reservoir" and that "no consistent seasonal differences in benthic populations were measured at sampling locations within areas influenced by the thermal discharge of the Allen Station versus locations which were not" [6].

## Fish

A list of fish species collected by the North Carolina Wildlife Resources Commission in 1965 and by Industrial Bio-Test Laboratories in 1973-74 are presented in Table 4. Based on these studies 45 species representing 10 families have been recorded from Lake Wylie [6] [10]. Numbers of species reported for the two studies are similar (Table 3) indicating no major shift in species composition had occurred during this time period.

Results of the year-long fish study of Lake Wylie conducted by Industrial Bio-Test showed that the total catches of fish (excluding threadfin shad) by gill netting and electroshocking were greater in the discharge cove than in any other location sampled [6] (see Figure 7 for sampling locations). Even though monthly average discharge temperatures reached 100.0°F (37.8°C) during the 1973-74 study period, the number of fish species collected from the elevated temperature region, except the discharge canal, was equal to or greater than that collected from outside the heat-affected area [6]. It is generally hypothesized that a shift in fish composition from sport to either forage or rough fish or both is usually associated with increased thermal loading. This was not observed in Lake Wylie where gill net catch rates of sport fish during all seasons were generally greater in the Allen discharge cove than in all other locations sampled [6]. These findings show that the Allen discharge temperatures outside the discharge canal did not limit fish abundance or diversity.

Fish distribution in Lake Wylie was dependent on a variety of factors including the suitability of habitat. This seemed to be especially true for sunfishes which were collected in greatest numbers from downlake locations. Redbreast sunfish and pumpkinseeds were more abundant at sampling locations outside the thermal influence of Plant Allen. All other sunfishes were either more abundant or equally abundant in the heat-affected zone when compared with the other uplake sampling location at the Allen intake area. White crappie were not found at any of the uplake sampling areas indicating lack of suitable habitat rather than thermal avoidance. Based on the above discussion, it appears that the lower (downlake) portion of Lake Wylie is a more suitable sunfish habitat. There is some avoidance of the heat-affected zone by some sunfish species and an attraction to it by others. The overall result is that there are more sunfish by numbers and by weight in the heat-affected zone (excluding the discharge canal itself) than in a comparable uplake area unaffected by heat.

Water temperatures in the South Fork Catawba River Arm of Lake Wylie receiving the Plant Allen condenser cooling water were 8.9°F (4.9°C) to 19.2°F (12.0°C) higher than those of the naturally occurring Catawba River Arm during the year-long Bio-Test study. Historically, monthly average condenser discharge temperatures as high as 101.6°F (38.7°C) have been recorded. Field fish body temperature studies and laboratory temperature avoidance studies were conducted to determine if fish were able to utilize areas influenced by the Allen thermal plume. Results of these studies showed that "consistent, though small, differences between fish body temperature and water temperature indicated that fish utilized both heated and unheated areas of the thermally stratified Allen discharge cove" even when temperatures exceeded 95°F (35°C) [6]. Oxygen concentrations and thermal conditions beneath the plume were always sufficient to support fish life and did not serve as a barrier to fish movement. These findings demonstrate that a substantial zone of unrestricted fish passage exists in the Allen discharge cove (South Fork Arm) and also that the fish move into and out of the plume at all times of the year, i.e., no thermal blockage was found to exist.

The heated effluent from Plant Allen allows threadfin shad, an extremely important forage fish, to survive the naturally occurring lower lethal winter temperatures, thereby reducing the need for perpetual restocking [6]. Lake Wylie threadfin shad populations serve as a major source for stocking other lakes in North Carolina.

Fish living in the elevated temperature regions may exhibit increased metabolic rates and, depending on food availability, this may result in a reduction of the K factor. No significant differences were found in the K factors of fishes located inside and outside the heat-affected zones [6]. It was further concluded that "any increase in the metabolic rate of fish in the Allen discharge area was apparently compensated for by either an adequate food supply or the movement of fish to other areas to feed" [6]. No difference in the growth rates of bluegill and redbreast sunfish was noted between heat-affected and unaffected populations.

The fish of Lake Wylie are typical warm water, non-migratory lake species that will spawn where suitable habitat exists. Peak spawning activity of most species studied occurred during the expected times throughout the study area; however, some species such as shad, quillbacks and white catfish apparently reached spawning conditions earlier in the Allen discharge than elsewhere [6]. The few white bass larvae obtained during the study were collected from the Allen discharge canal, indicating that they were able to successfully utilize the Allen discharge for spawning; and, also, that the heated effluent was not a barrier to their migration [6]. None of the above-mentioned effects can be considered detrimental to Lake Wylie fish populations.

Larval fish sampling by Bio-Test [6] indicated that the greatest densities existed from April through June in 1974. A total of 10 taxa were identified, including shad, largemouth bass, crappie, and other sunfish. The greatest numbers of larval fish were shad. Larvae of the major sport and forage fish were collected in the immediate discharge area of Allen indicating that the temperatures during the critical spawning period were not too high to exclude fish from this area.

The incidence of external parasitic infestations was low at all sampling stations [6]. Epistylis, an external parasite, was observed on fish during all months of the study and from all areas sampled. It was found to occur slightly more frequently at the Allen discharge areas. Since Epistylis is found more frequently in areas of organic enrichment, the increased incidence of infection may be due to the enriched condition of the South Fork.

308<

A study of gas bubble disease conducted by the North Carolina Wildlife Resources Commission revealed a low incidence of the disease in Lake Wylie [11]. Of the 1305 fish examined only three exhibited external symptoms of gas bubble disease [11]. No symptoms of gas bubble disease were observed in fish collected during the Bio-Test study [6].

Since Allen has five independently operating units, it is improbable that all units will be shut down at the same time. No evidence of cold shock has been observed and no cold shock is expected.

## SUMMARY AND CONCLUSION

The results of the ecological research conducted on Lake Wylie and contained in Duke's 316(a) Demonstration are best summarized by EPA's major findings of fact. These findings were that Plant Allen, in its present once-through operating mode, will assure the propagation of a balanced indigenous population in and on Lake Wylie. The information presented in Duke's 316(a) Demonstration was used as a basis for modifying the Plant Allen NPDES discharge permit requiring cooling towers to no cooling towers and the following: 1) a monthly maximum discharge temperature of 38.9°C (102.0°F), and 2) a 24-hour average discharge temperature of 40.2°C (104.3°F). The evolution of thermal standards to the present form providing for 316(a) Demonstrations has, in effect, led us full circle back to the "Green Book." Even though two more extensively researched and more detailed efforts were made to update and set national thermal standards, the "Green Book" admonition appears to be more appropriate than ever in stating that "in view of the many variables, it seems obvious that no single temperature requirement can be applied to the United States as a whole, or even to one State."

## REFERENCES

1. U. S. Department of the Interior. 1968. Water Quality Criteria, A Report of the National Technical Advisory Committee to the Secretary of the Interior. U. S. Government Printing Office, Washington, D. C. 234 pp.

2. U. S. Environmental Protection Agency. 1972. Water Quality Criteria. National Academy of Sciences and National Academy of Engineering. U. S. Government Printing Office, Washington, D. C. 594 pp.

3. U. S. Environmental Protection Agency. In Press. Quality Criteria for Water. U. S. Government Printing Office, Washington, D. C.

4. Federal Water Pollution Control Acts. Amendments of 1972, Public Law 92-500.

5. Duke Power Company. 1976. Plant Allen, 316(a) Demonstration. Charlotte, North Carolina.

6. Industrial Bio-Test. 1974. A baseline/predictive environmental investigation of Lake Wylie. Volumes I, II. Prepared for Duke Power Company, Charlotte, North Carolina.

7. Ryan, P. J., and D. R. F. Harleman. 1973. An analytical and experimental study of transient cooling pond behavior. Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Report Number 161, M.I.T.

8. Weiss, C. M., P. H. Campbell, T. P. Anderson, and S. L. Pfaender. 1975. The Lower Catawba Lakes: characterization of phyto- and zooplankton communities and their relationships to environmental factors. University of North Carolina, Chapel Hill. Department of Environmental Sciences and Engineering Publication Number 389.

9. Lenat, D. R., and C. M. Weiss. 1973. Distribution of benthic macroinvertebrates in Lake Wylie, North Carolina-South Carolina. University of North Carolina, Chapel Hill, Department of Environmental Sciences and Engineering Publication Number 311.

10. McNaughton, W. C. 1965. Upper Catawba and Upper Yadkin River reservoirs. North Carolina Wildlife Resources Commission.

11. Miller, R. W. 1974. Incidence and cause of gas-bubble disease in a heated effluent. pp. 79-93. In J. W. Gibbons and R. R. Sharitz (eds) Thermal Ecology. U. S. Atomic Energy Commission Symposium Series, Conf. 730505 (1973).

## TABLE I

### Recent Plant Allen Monthly Average Inlet Temperature, Condenser Delta T and Average Outlet Temperature Compilations

| Month | Year | Average Inlet Temperature °F(°C) | Plant Delta T °F(°C) | Average Outlet Temperature °F(°C) |
|---|---|---|---|---|
| January | 1968 | 43.5(6.4) | 23.0(12.8) | 66.5(19.2) |
| February | | 44.2(6.8) | 25.8(14.3) | 70.0(21.2) |
| March | | 52.2(11.2) | 20.8(11.6) | 73.0(22.8) |
| April | | 64.1(17.8) | 16.2(9.0) | 80.3(26.8) |
| May | | 71.1(21.7) | 15.1(8.4) | 86.2(30.1) |
| June | | 78.5(25.8) | 15.4(8.6) | 93.9(34.4) |
| July | | 82.4(28.0) | 16.2(9.0) | 98.6(37.0) |
| August | | 84.5(29.2) | 17.1(9.5) | 101.6(38.7) |
| September | | 78.6(25.9) | 16.3(9.1) | 94.9(34.9) |
| October | | 71.0(21.7) | 14.7(8.2) | 85.7(29.8) |
| November | | 57.5(14.2) | 17.9(9.9) | 75.4(24.1) |
| December | | 48.6(9.2) | 19.3(10.7) | 67.9(19.9) |
| January | 1969 | 44.7(7.1) | 22.5(12.5) | 67.2(19.6) |
| February | | 46.2(7.9) | 23.1(12.9) | 69.3(20.7) |
| March | | 49.2(9.6) | 20.3(11.3) | 69.5(20.8) |
| April | | 61.6(16.4) | 17.3(9.6) | 78.9(26.1) |
| May | | 70.4(21.3) | 15.7(8.7) | 86.1(30.1) |
| June | | 77.9(25.5) | 13.7(7.6) | 91.6(33.1) |
| July | | 84.6(29.2) | 14.8(8.2) | 99.4(37.4) |
| August | | 82.4(28.0) | 16.0(8.9) | 98.4(36.9) |
| September | | 78.1(25.6) | 13.7(7.6) | 91.8(33.2) |
| October | | 70.1(21.2 | 14.2(7.9) | 84.3(29.1) |
| November | | 57.7(14.3) | 22.0(12.2) | 79.7(26.5) |
| December | | 47.9(8.8) | 19.3(10.7) | 67.2(19.6) |
| January | 1970 | 43.2(6.2) | 23.5(13.1) | 66.7(19.3) |
| February | | 46.2(7.9) | 23.1(12.8) | 69.3(20.7) |
| March | | 52.9(11.6) | 20.7(11.5) | 73.6(23.1) |
| April | | 62.5(16.9) | 15.8(8.8) | 78.3(25.7) |
| May | | 71.6(22.0 | 16.2(9.0) | 87.8(31.0) |
| June | | 79.2(26.2) | 14.5(8.1) | 93.7(34.3) |
| July | | 82.4(28.0) | 14.5(8.1) | 96.9(36.1) |
| August | | 86.4(30.2) | 14.9(8.3) | 101.3(38.5) |
| September | | 80.4(26.9) | 16.8(9.3) | 97.2(36.2) |
| October | | 72.1(22.3) | 15.5(8.6) | 87.6(30.9) |
| November | | 59.3(15.2) | 15.8(8.8) | 75.1(23.9) |
| December | | 51.9(11.1) | 17.6(9.8) | 69.5(20.8) |

## TABLE I, Continued

| Month | Year | Average Inlet Temperature °F(°C) | Plant Delta T °F(°C) | Average Outlet Temperature °F(°C) |
|---|---|---|---|---|
| January | 1971 | 46.0(7.8) | 23.6(13.1) | 69.6(20.9) |
| February | | 44.2(6.8) | 16.8(9.3) | 61.0(16.1) |
| March | | 50.7(10.4) | 19.2(10.7) | 69.9(21.1) |
| April | | 59.3(15.2) | 16.0(8.9) | 75.3(24.1) |
| May | | 67.6(19.8) | 15.8(8.8) | 83.4(28.6) |
| June | | 74.5(23.6) | 16.7(9.3) | 91.2(32.9) |
| July | | 81.6(27.6) | 15.1(8.4) | 96.7(35.9) |
| August | | 82.7(28.7) | 15.9(8.8) | 98.6(37.0) |
| September | | 80.3(26.8) | 14.4(8.0) | 94.7(34.8) |
| October | | 71.5(21.9) | 14.1(7.8) | 85.6(29.8) |
| November | | 61.0(16.1) | 17.3(9.6) | 78.3(25.7) |
| December | | 52.1(11.2) | 16.9(9.4) | 69.0(20.6) |
| January | 1972 | 50.4(10.2) | 18.3(10.2) | 68.7(20.4) |
| February | | 46.6(8.1) | 23.7(13.2) | 70.3(21.3) |
| March | | 53.2(11.8) | 20.5(11.4) | 73.7(23.2) |
| April | | 61.6(16.4) | 17.4(9.7) | 79.0(26.1) |
| May | | 69.9(21.1) | 14.7(8.2) | 84.6(29.2) |
| June | | 75.4(24.1) | 11.8(6.6) | 87.2(30.7) |
| July | | 81.2(27.4) | 14.0(7.8) | 95.2(35.1) |
| August | | 82.8(28.2) | 15.8(8.8) | 98.6(37.0) |
| September | | 79.4(26.4) | 15.2(8.4) | 94.6(34.8) |
| October | | 69.0(20.6) | 15.4(8.6) | 84.4(29.1) |
| November | | 59.6(15.3) | 19.9(11.1) | 79.5(26.4) |
| December | | 50.9(10.5) | 18.3(10.2) | 69.2(20.7) |
| January | 1973 | 46.9(8.3) | 18.6(10.3) | 65.5(18.6) |
| February | | 45.9(7.7) | 18.5(10.3) | 64.4(18.0) |
| March | | 51.6(10.9) | 18.6(10.3) | 70.2(21.2) |
| April | | 57.4(14.1) | 18.4(10.2) | 75.8(24.3) |
| May | | 65.9(18.8) | 18.5(10.3) | 84.4(29.1) |
| June | | 76.1(24.5) | 18.7(10.4) | 94.8(34.9) |
| July | | 82.3(27.9) | 18.9(10.5) | 101.2(38.4) |
| August | | 82.9(28.3) | 18.7(10.4) | 101.6(38.7) |
| September | | 81.1(27.3) | 18.9(10.5) | 100.0(37.8) |
| October | | 72.5(22.5) | 19.5(10.8) | 89.6(32.0) |
| November | | 60.5(15.8) | 19.2(10.7) | 79.7(26.5) |
| December | | 50.7(10.4) | 20.5(11.4) | 71.2(21.8) |
| January | 1974 | 50.1(10.1) | 19.3(10.7) | 69.5(20.8) |
| February | | 49.6(9.8) | 19.3(10.7) | 68.9(20.5) |
| March | | 54.1(12.3) | 19.0(10.6) | 73.0(22.8) |
| April | | 60.1(15.6) | 18.7(10.4) | 78.7(25.9) |
| May | | 69.3(20.7) | 20.8(11.6) | 89.4(31.9) |

## TABLE I, Continued

| Month | Year | Average Inlet Temperature °F(°C) | Plant Delta T °F(°C) | Average Outlet Temperature °F(°C) |
|---|---|---|---|---|
| June | 1974 | 77.3(25.2) | 17.2(9.6) | 94.5(34.7) |
| July | | 80.8(27.1) | 16.9(9.4) | 97.7(36.5) |
| August | | 81.5(27.5) | 16.3(9.1) | 97.8(36.6) |
| September | | 76.3(24.6) | 16.7(9.3) | 93.1(33.9) |
| October | | 66.9(19.4) | 19.1(10.6) | 86.0(30.0) |
| November | | 59.1(15.1) | 17.2(9.6) | 76.3(24.6) |
| December | | 47.7(8.7) | 17.1(9.5) | 64.8(18.2) |

214<

DWA

TABLE 2. PLANT ALLEN MONTHLY AVERAGE THERMAL PLUME DATA - PREDICTED

| Reference Extreme Figure | | Plant Operating Conditions: Condenser Flow | T | Load[1] | Thermal Plume Data, 90°F (32°C) Isotherm: Intake[2] Temp. | Discharge Temp. | N. C. Surface | S. C. Surface | Total[5] Surface | % N. C.[3] Lake | % S. C.[3] Lake | % Total[5] Lake | N. C. Shoreline | S. C. Shoreline | Total[5] Shoreline | % N. C.[4] Lake | % S. C.[4] Lake | % Total[5] Lake |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | cfs | °F(°C) | % | °F(°C) | °F(°C) | Acres | Acres | Acres | Acreage | Acreage | Acreage | Miles | Miles | Miles | Shoreline | Shoreline | Shoreline |
| Figure 8 | Winter | 803 | 29(16.1) | 100 | 52(11.1) | 81(27.2) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Figure 9 | Summer | 1334 | 18(10) | 100 | 85(29.4) | 103(39.4) | 670 | 430 | 1100 | 10% | 8% | 9% | 12.5 | 1.5 | 14 | 5% | 2% | 4% |

| Reference Extreme Figure | | 5°F(2.8°C) Excess ABOVE INTAKE ISOTHERM: N. C. Surface | Total[5] Surface | % N. C. Lake | % Total[5] Lake | N. C. Shoreline | Total[5] Shoreline | % N. C. Lake | % Total[5] Lake | 3°F(1.7°C) Excess ABOVE INTAKE ISOTHERM: S. C. Surface | Total[5] Surface | % S. C. Lake | % Total[5] Lake | S. C. Shoreline | Total[5] Shoreline | % S. C. Lake | % Total[5] Lake |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Acres | Acres | Acreage | Acreage | Miles | Miles | Shoreline | Shoreline | Acres | Acres | Acreage | Acreage | Miles | Miles | Shoreline | Shoreline |
| Figure 8 | Winter | 1100 | 1950 | 16% | 16% | 17.5 | 25 | 8% | 8% | 1100 | 2800 | 20% | 22% | 9.5 | 34 | 10% | 10% |
| Figure 9 | Summer | 670 | 1100 | 10% | 9% | 12.5 | 14 | 5% | 4% | 720 | 1850 | 13% | 15% | 6 | 20.5 | 6% | 6% |

[1] PLANT full load operating capacity = 1155 MW

[2] Based on maximum monthly average intake temperatures selected from period 1960-1970; winter-December, 1967; summer-August. 1968.

[3] Based on full pond lake elevation at 569.4 msl (12,455 acres); lake surface acreage in N. C. and S. C. are respectively 6,975 and 5,480 acres.

[4] Based on total shoreline mileage of 327 miles; 232 miles in N. C. and 95 miles in S. C.

[5] Total refers to sum of affected areas in both North and South Carolina.

## TABLE 3

### COMMON AND SCIENTIFIC NAMES OF FISHES COLLECTED FROM LAKE WYLIE, NORTH AND SOUTH CAROLINA

| Family<br>Species | Common Name | N.C.W.R.C.[1] Study | Bio-Test Study |
|---|---|---|---|
| Lepisosteidae - Gars | | | |
| Lepisosteus osseus (Linnaeus) | Longnose Gar | X | X |
| Amiidae - Bowfins | | | |
| Amia calva (Linnaeus) | Bowfin | X | X |
| Clupeidae - Herrings | | | |
| ** Dorosoma cepedianum (LeSueur) | Gizzard Shad | X | X |
| ** Dorosoma petenense (Gunther) | Threadfin Shad | X | X |
| Cyprinidae - Minnows and Carps | | | |
| Carassius auratus (Linnaeus) | Goldfish | X | X |
| Cyprinus carpio Linnaeus | Carp | X | X |
| Hybognathus nuchalis Agassiz | Silvery Minnow | | X |
| Nocomis leptocephalus (Girard) | Bluehead Chub | | X |
| Notemigonus crysoleucas (Mitchill) | Golden Shiner | X | X |
| Notropis analostanus (Girard) | Satinfin Shiner | X | X |
| Notropis hudsonis (Clinton) | Spottail Shiner | X | X |
| Notropis procne (Cope) | Swallowtail Shiner | X | X |
| Catostomidae - Suckers | | | |
| Carpiodes carpio (Rafinesque) | River Carpsucker | | X |
| Carpiodes cyprinus (LeSueur) | Quillback | X | X |
| Catostomus commersoni (Lacepede) | White Sucker | X | X |
| Erimyzon oblongus (Mitchill) | Creek Chubsucker | | X |
| Erimyzon sucetta (Lacepede) | Lake Chubsucker | X | |
| Ictiobus bubalus (Rafnisque) | Samllmouth Buffalo | X | X |
| Ictiobus cyprinellus (Valenciennes) | Bigmouth Buffalo | | X |
| Moxostoma collapsum (Cope) | V-lip Redhorse | X | |
| Moxostoma macrolepidotum (LeSueur) | Shorthead Redhorse | | X |
| Moxostoma pappillosum (Cope) | Suckermouth Redhorse | X | X |
| Moxostoma robustum (Cope) | Smallfin Redhorse | | X |
| Ictaluridae - Freshwater Catfishes | | | |
| Ictalurus catus (Linnaeus) | White Catfish | X | X |
| Ictalurus melas (Rafinesque) | Black Bullhead | | X |
| Ictalurus natalis (LeSueur) | Yellow Bullhead | X | |
| Ictalurus nebulosus (LeSueur) | Brown Bullhead | X | X |
| Ictalurus platycephalus (Girard) | Flat Bullhead | | X |
| Ictalurus punctatus (Rafinesque) | Channel Catfish | X | X |
| Poeciliidae - Livebearers | | | |
| Gambusia affinis (Baird and Girard) | Mosquitofish | | X |
| Perichthyidae - Temperate Basses | | | |
| * Morone chrysops (Rafinesque) | White Bass | X | X |
| Centrarchidae - Sunfishes | | | |
| * Ambloplites rupestris (Rafinesque) | Rock Bass | | X |
| * Enneacanthus gloriosus (Holbrook) | Bluespotted Sunfish | X | |
| * Lepomis auritus (Linnaeus) | Redbreast Sunfish | X | X |
| * Lepomis cyanellus (Rafinesque) | Green Sunfish | X | |

| Family<br>Species | Common Name | N.C.W.R.C.[1] Study | Bio-Test Study |
|---|---|---|---|
| Centrarchidae - Sunfishes | | | |
| * *Lepomis gibbosus* (Linnaeus) | Pumpkinseed | X | X |
| * *Lepomis gulosus* (Cuvier) | Warmouth | X | X |
| * *Lepomis macrochirus* Rafinesque | Bluegill | X | X |
| * *Lepomis microlophus* (Gunther) | Redear Sunfish | | X |
| * *Micropterus salmoides* (Lacepede) | Largemouth Bass | X | X |
| * *Pomoxis annularis* Rafinesque | White Crappie | X | X |
| * *Pomoxis nigromaculatus* (LeSueur) | Black Crappie | X | X |
| Percidae | | | |
| *Etheostoma nigrum* Rafinesque | Johnny Darter | X | X |
| * *Perca flavescens* (Mitchill) | Yellow Perch | X | X |
| *** *Stizostedium vitreum* (Mitchill) | Walleye | X | |

---

[1] North Carolina Wildlife Resources Commission

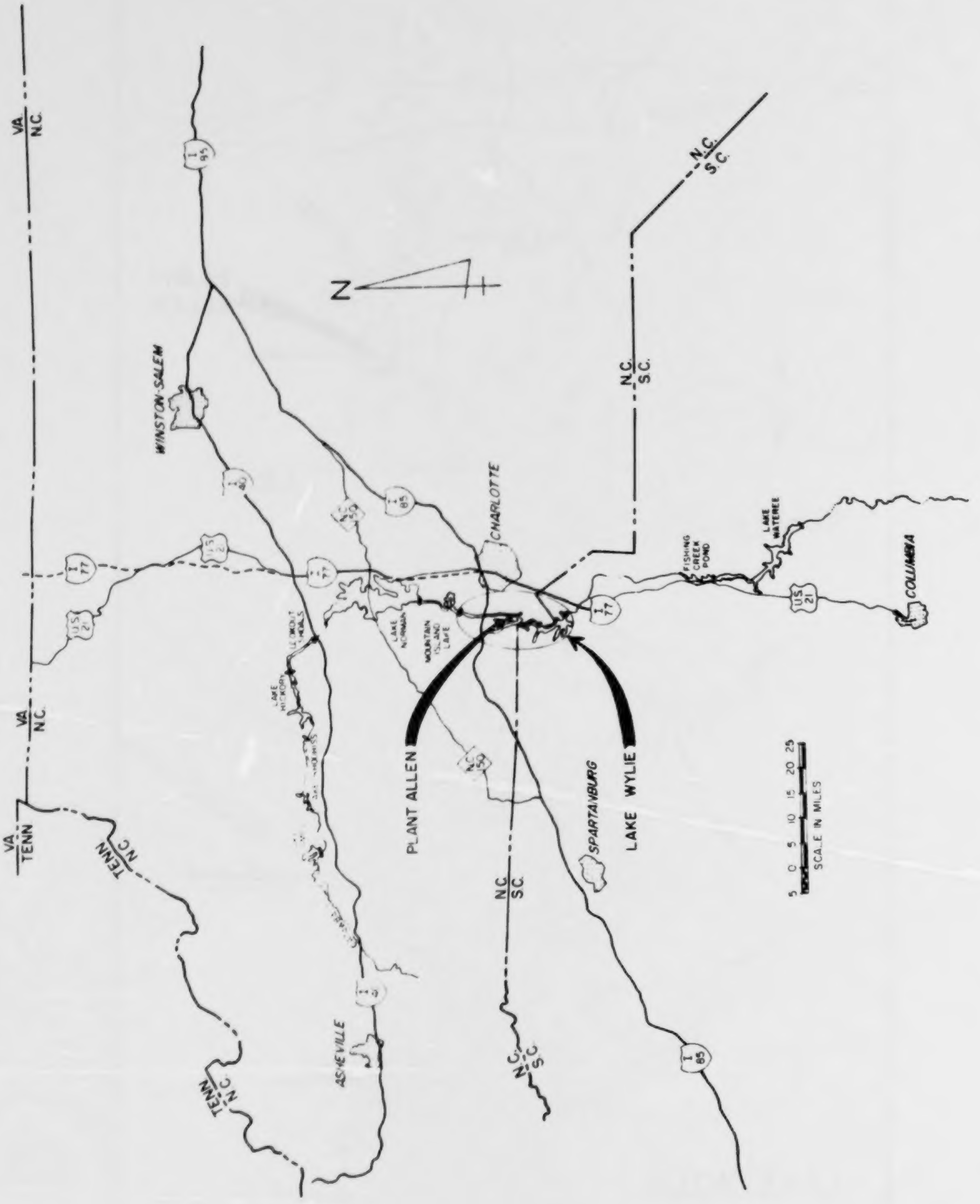
* Important Game or Pan Fish

** Important Forage Fish

*** Stocked - 1954

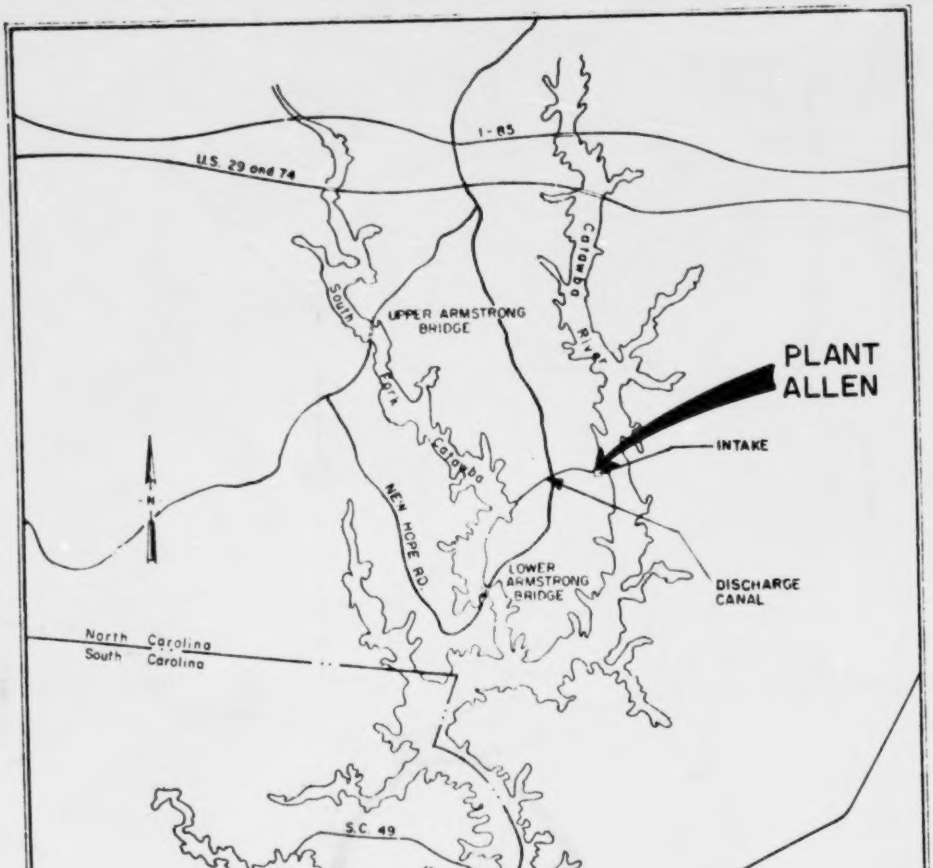
216<

DWA


VA.
N.C.
VA.
TENN
TENN
N.C.
N
WINSTON-SALEM
CHARLOTTE
ASHEVILLE
SPARTANBURG
COLUMBIA
LAKE NORMAN
MOUNTAIN ISLAND LAKE
LAKE HICKORY
LOOKOUT SHOALS
FISHING CREEK POND
LAKE WATEREE
PLANT ALLEN
LAKE WYLIE
N.C.
S.C.
I 95
I 85
I 40
I 77
US 21
US 52
NC 150
5 0 5 10 15 20 25
SCALE IN MILES

REGIONAL SITE LOCATION

**PLANT ALLEN**
Figure 1

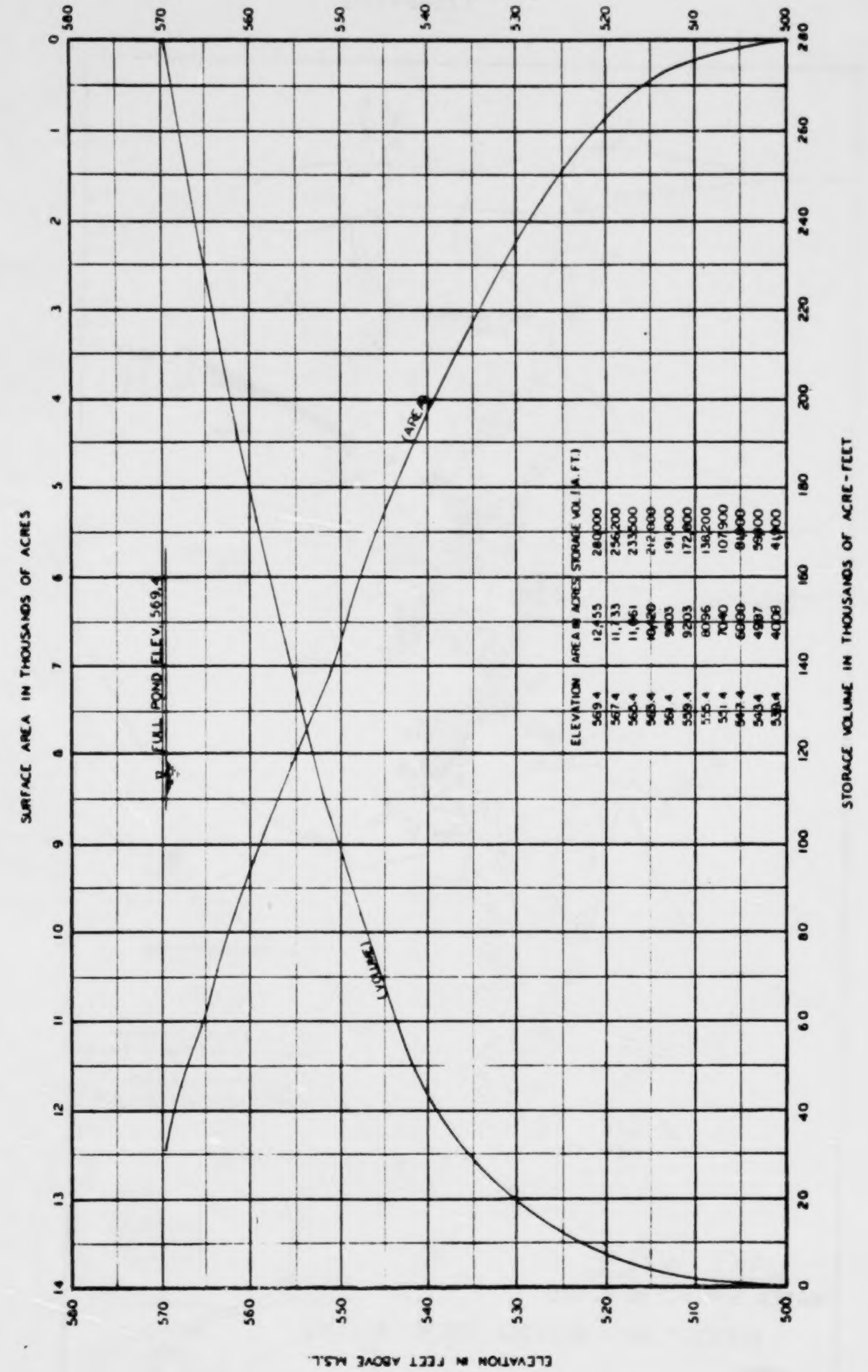

I-85
U.S. 29 and 74
Catawba River
South Fork Catawba
UPPER ARMSTRONG BRIDGE
PLANT ALLEN
INTAKE
N
NEW HOPE RD.
DISCHARGE CANAL
LOWER ARMSTRONG BRIDGE
North Carolina
South Carolina
S.C. 49
N.C. 49
North Carolina
South Carolina
0 1 2
SCALE IN MILES
WYLIE STATION
LAKE WYLIE

MAP OF LAKE WYLIE

**PLANT ALLEN**
Figure 2

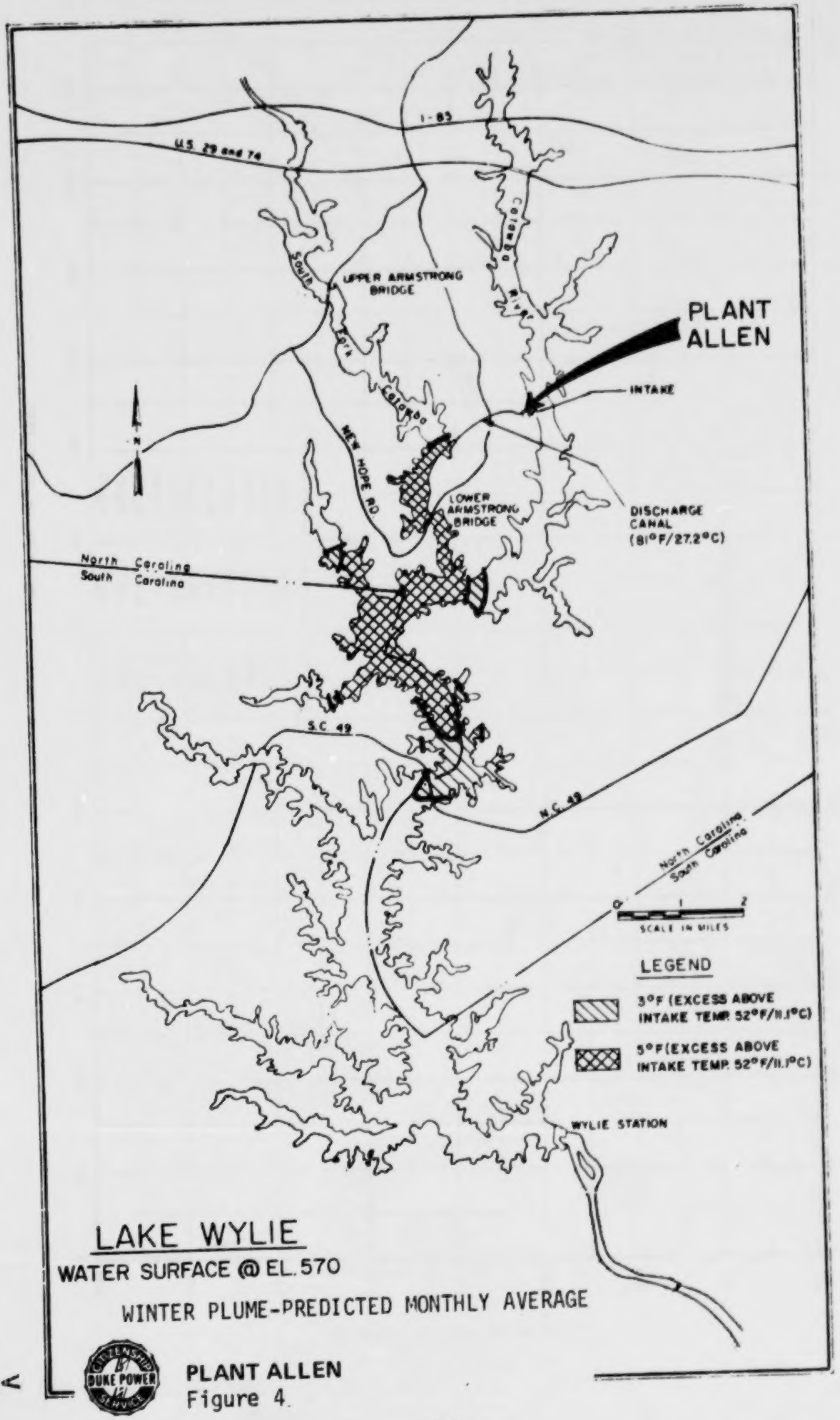
318<

DWA

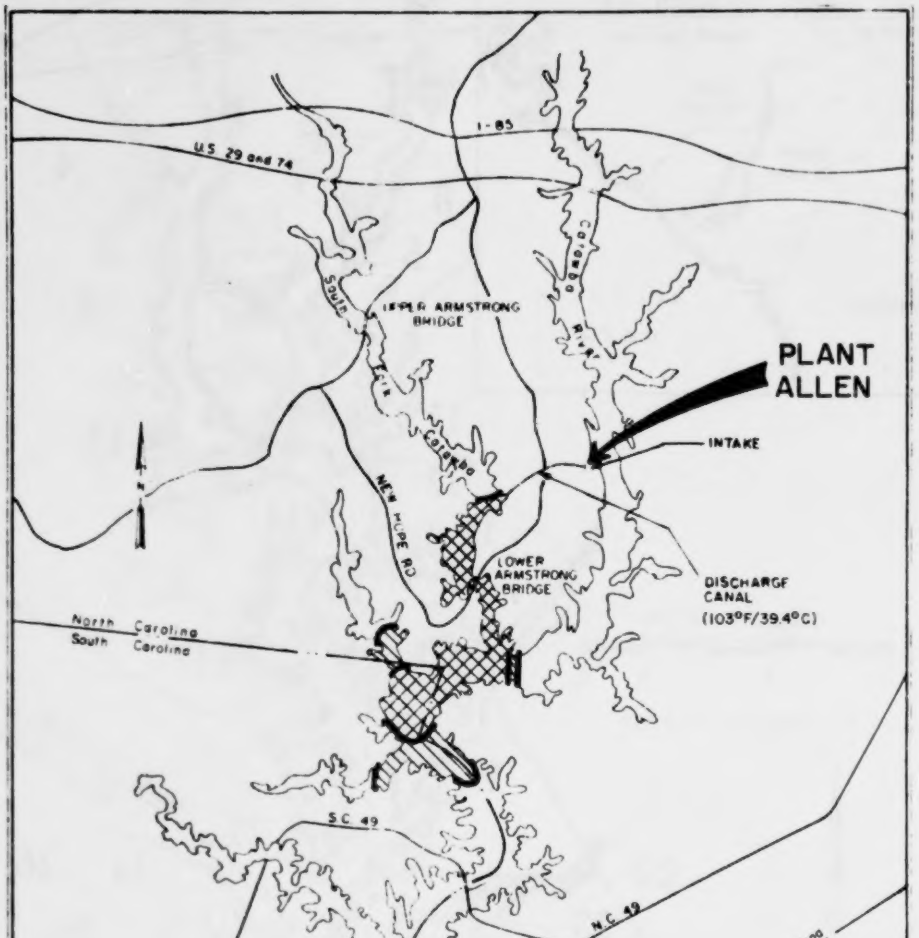


LAKE WYLIE AREA AND VOLUME CURVES

**PLANT ALLEN**
Figure 3


I-85
U.S. 29 and 74
Catawba River
South Fork Catawba
UPPER ARMSTRONG BRIDGE
PLANT ALLEN
INTAKE
N
NEW HOPE RD
LOWER ARMSTRONG BRIDGE
DISCHARGE CANAL (81°F/27.2°C)
North Carolina
South Carolina
S.C. 49
N.C. 49
North Carolina
South Carolina
0 1 2
SCALE IN MILES
LEGEND
3°F (EXCESS ABOVE INTAKE TEMP. 52°F/11.1°C)
5°F (EXCESS ABOVE INTAKE TEMP. 52°F/11.1°C)
WYLIE STATION
LAKE WYLIE
WATER SURFACE @ EL.570
WINTER PLUME-PREDICTED MONTHLY AVERAGE

**PLANT ALLEN**
Figure 4


I-85
U.S. 29 and 74
South Fork Catawba
Catawba River
UPPER ARMSTRONG BRIDGE
PLANT ALLEN
INTAKE
N
NEW HOPE RD
LOWER ARMSTRONG BRIDGE
DISCHARGE CANAL (103°F/39.4°C)
North Carolina
South Carolina
S.C. 49
N.C. 49
North Carolina
South Carolina
0 1 2
SCALE IN MILES
LEGEND
▨ 3° F (EXCESS ABOVE INTAKE TEMP. 85°F/29.4°C)
▩ 90°F & 5°F (EXCESS ABOVE INTAKE TEMP. 85°F/29.4°C)
WYLIE STATION

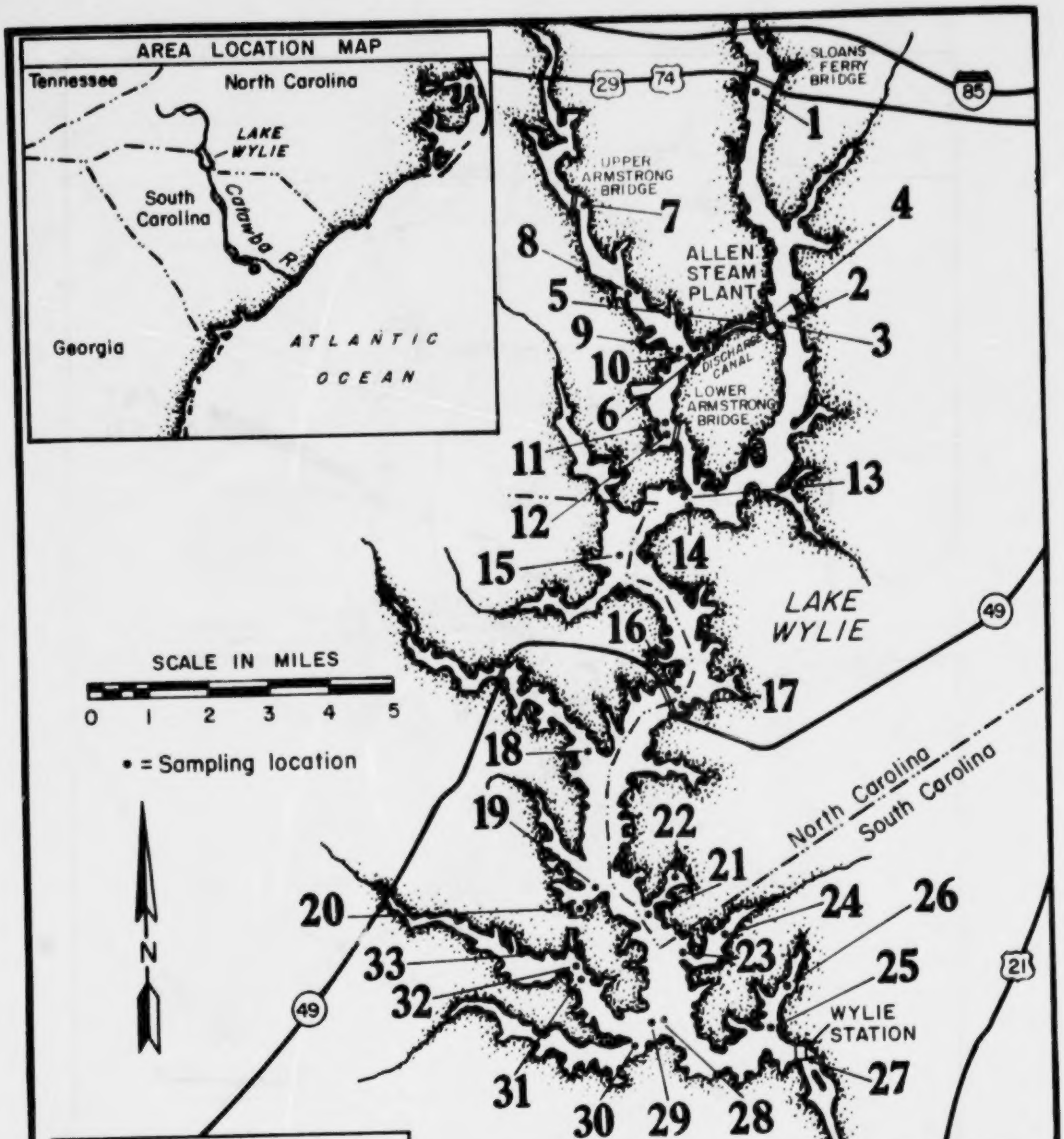
LAKE WYLIE

WATER SURFACE @ EL.570

SUMMER PLUME-PREDICTED MONTHLY AVERAGE

PLANT ALLEN
Figure 5

321<

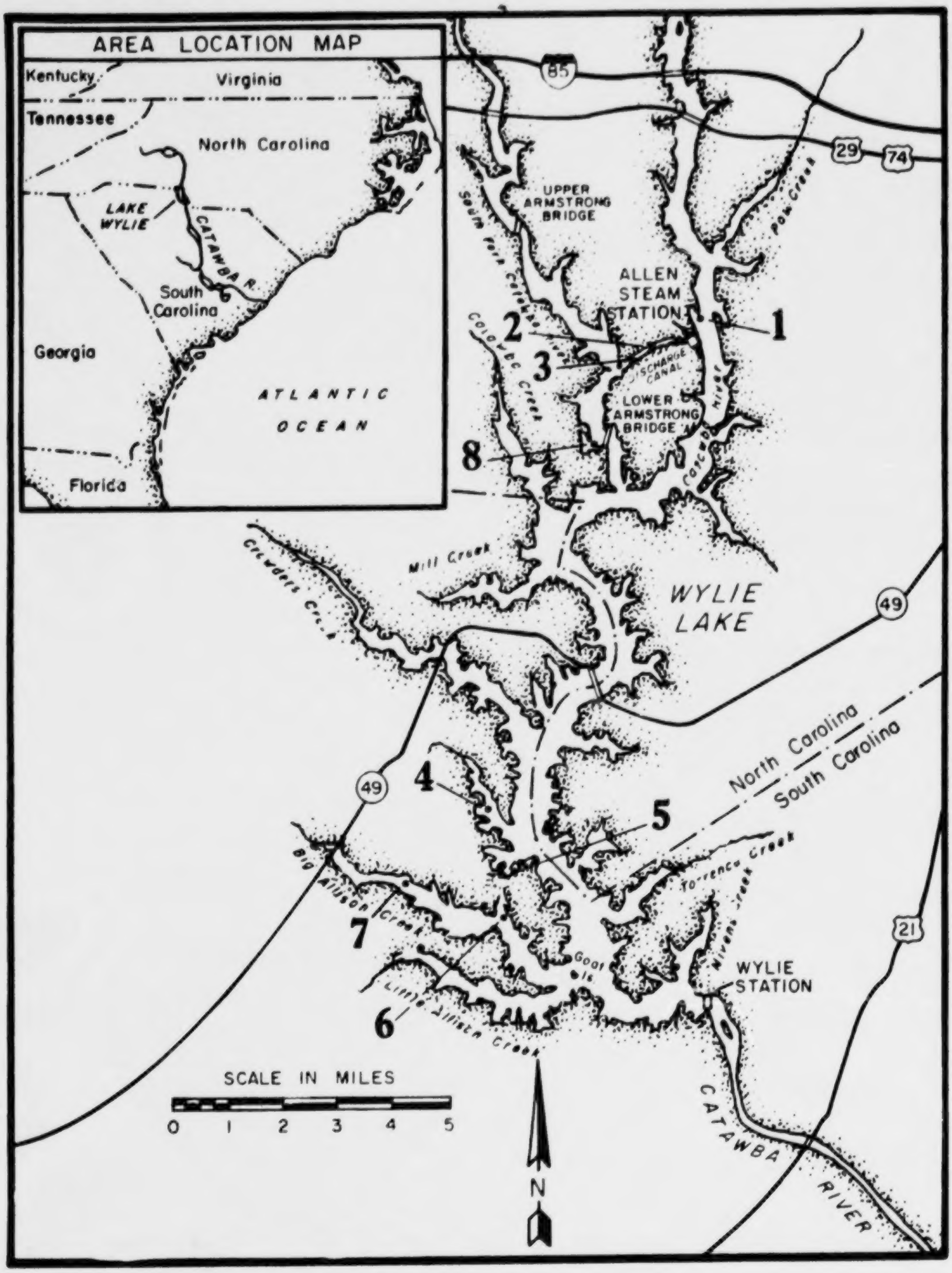

AREA LOCATION MAP
Tennessee
North Carolina
LAKE WYLIE
South Carolina
Catawba R.
Georgia
ATLANTIC OCEAN
29
74
85
SLOANS FERRY BRIDGE
UPPER ARMSTRONG BRIDGE
ALLEN STEAM PLANT
DISCHARGE CANAL
LOWER ARMSTRONG BRIDGE
LAKE WYLIE
49
21
North Carolina
South Carolina
WYLIE STATION
SCALE IN MILES
0 1 2 3 4 5
• = Sampling location
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33

| LEGEND | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BENTHIC INVERTEBRATES | FEB, APR-AUG, OCT, DEC | | ● | ● | | | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | | | | | | | | ● | ● | ● | | ● | ● | |
| | QUALITATIVE SAMPLES | | ● | | | | | | | | ● | | ● | | ● | | | ● | | ● | | | | | | | | | | | | | ● | |
| | QUARTERLY SAMPLES | | | | | | | | | | | | | | | | | | | | ● | | | | | | | | | | | | | ● |
| PERIPHYTON | | | | ● | | | | | | | ● | | ● | | | | ● | | | ● | | | | | | | | | | | | ● | | |
| PHYTOPLANKTON (Monthly) | 1M. BENEATH SURFACE | | ● | | | | | ● | ● | | ● | | ● | | ● | ● | | ● | | ● | | | | | | | | ● | ● | | | | ● | |
| | 1M. ABOVE BOTTOM | | ● | | | | | | ● | | ● | | | | ● | ● | | ● | | ● | | | | | | | | | | | | | ● | |
| PROFILE & DIURNAL SAMPLES (QUARTERLY) | | | ● | | | | | | | | ● | | ● | | | | | | | | | | | | | | | | | | | | | |
| ZOOPLANKTON (Monthly) | 3M. TO SURFACE | | ● | | | | | | ● | | ● | | | | | ● | | ● | | ● | | | | | | | | | | | | | ● | |
| | BOTTOM TO SURFACE | | ● | | | | | ● | ● | | ● | | ● | | ● | ● | | ● | | ● | | | | | | | | ● | ● | | | | ● | |
| PROFILE & DIURNAL SAMPLES (QUARTERLY) | | | ● | | | | | | | | ● | | ● | | | | | | | | | | | | | | | | | | | | | |
| CHEMISTRY | | ● | ● | ● | | | | ● | ● | ● | ● | | ● | | ● | ● | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | | ● | ● |

SAMPLING LOCATIONS FOR BENTHIC INVERTEBRATES,
PERIPHYTON, PHYTOPLANKTON, ZOOPLANKTON AND
WATER QUALITY (FROM REFERENCE 6)

322<

**PLANT ALLEN**
Figure 6


AREA LOCATION MAP
Kentucky
Virginia
Tennessee
North Carolina
LAKE WYLIE
CATAWBA R.
South Carolina
Georgia
ATLANTIC OCEAN
Florida
85
29
74
UPPER ARMSTRONG BRIDGE
ALLEN STEAM STATION
1
2
3
DISCHARGE CANAL
LOWER ARMSTRONG BRIDGE
South Fork Catawba River
Catawba River
Paw Creek
Catawba Creek
8
Mill Creek
Crowders Creek
WYLIE LAKE
49
North Carolina
South Carolina
4
5
Torrence Creek
Big Allison Creek
7
6
Little Allison Creek
Goat Is.
Sugar Creek
WYLIE STATION
21
SCALE IN MILES
0 1 2 3 4 5
N
CATAWBA RIVER

FISH SAMPLING LOCATIONS (FROM REFERENCE 6)

323<

**PLANT ALLEN**
Figure 7

DWA

# SESSION III-C

# COOLING SYSTEMS II

1 - omit

III-C-115

UNIVERSITY OF KENTUCKY
LEXINGTON, KENTUCKY 40506

COLLEGE OF ENGINEERING
DEPARTMENT OF MECHANICAL ENGINEERING

PHONE 606 258 2661

## Abstract

# COMPUTER ANALYSIS OF HEAT REJECTION SYSTEMS FOR COAL CONVERSION PROCESSES

by

Thomas E. Eaton, PE
and
Charles E. Duncan
Mechanical Engineering Department
University of Kentucky
January 1977

A literature search was conducted to determine the predictive methods available for analysis of the cooling needs of coal conversion systems. Principal factors of interest were cooling performance, water consumption, and environmental effects. The frequently proprietary nature of the computational details required that approximations be used in many of the computations. Further aggravation arose because computer codes were originally written for steam electric stations. Nevertheless, computer codes were obtained which could approximately predict size, water consumption and environmental effects of various cooling systems.

Coal conversion plants differ from electric utility generating stations in that they need not be required to operate at full capacity during extreme weather conditions. Furthermore, as would be expected. the heat rejection conditions and requirements differ considerably between coal conversion plants and electric generating stations (1).

With the available codes, various heat rejection systems were compared for a demonstration scale, coal gasification plant (2). The

comparison was based on full heat rejection capability in all but the most extreme 5% of Kentucky's weather conditions; the parameters and results of this comparison are given in Table 1.

For the demonstration coal gasification plant, a spray canal was found to have the lowest evaporative rate and a natural draft wet tower the greatest; the maximum evaporation of the latter system was twice that of the former. Although slightly higher with natural draft, the evaporation rates of the evaporative cooling towers were comparable. The dry, natural draft tower required for the case was nearly twice the height of the wet natural draft tower.

Although the computational results were comparable with existing heat rejection systems, the most promising methods for heat rejection from coal conversion plants was felt to be a hybrid system which takes advantage of both wet and dry cooling methods. Flexibility in cooling system design and operation should attempt to decrease the dependence of coal conversion plant siting on water availability. With this, coal transportation charges could be reduced or eliminated. Clearly, an economic trade-off exists between feedstock transportation and heat rejection system design when water availability influences coal conversion plant siting.

Phased cooling and staged cooling are both heat rejection techniques which could be used to allow flexibility in the search for coal conversion plant siting. Phased cooling is a technique which involves the storage of heat when active heat rejection capacity is exceeded. Staged cooling involves the simultaneous use of more than one heat rejection technique (3). Flexibility of system performance could be even further enhanced by combining a staged cooling system with a thermal storage system.

A promising staged cooling system was determined to be a dry cooling tower in combination with a spray canal. This combination along with other mixed-mode systems are being considered in more detail. Interesting aspects are the possibility of reversing the equipment operating order for series operation or changing the operating mode from series to the parallel mode. Mined-out areas are being considered as possible thermal storage facilities for coal conversion plant, phased cooling systems.

## References

(1) Gentry, E.L. and Eaton, T.E., "Water Requirements and Overall Efficiencies for Various Coal Conversion Processes,"Sixth Environmental Engineering and Science Conference, Louisville, Kentucky, February 1977.

(2) Duncan, Charles E., "A Computer Analysis of Heat Rejection Systems for Coal Conversion Processes," MSNE Thesis, Mechanical Engineering Department University of Kentucky, 1977.

(3) Guyer, E.C. and Golay, M.W., "An Engineering Evaluation of Some Mixed-Mode Waste Heat Rejection Systems," Department of Nuclear Engineering, Massachusetts Institute of Technology, Report No. MITNE-191, October 1976.

4

### Table 1

### RESULTS OF COMPUTER ANALYSIS

**Constant Parameters**

| | |
|---|---|
| Water Flow Rate | 60,000 GPM |
| Cooling Range | 33°F |
| Heat Rejection Rate | 5,000,000 BTU/hr |
| Elevation | 600 ft., Kentucky Climate |

**DRYTOWER**

| | Average Conditions | | Extreme Conditions | |
|---|---|---|---|---|
| Month | Air Temperature (°F) | Tower Height (ft) | Air Temperature (°F) | Tower Height (ft) |
| April | 55 | 425 | — | — |
| May | 65 | 445 | 68 | 450 |
| June | 74 | 461 | 76 | 465 |
| July | 77 | 466 | 78 | 468 |
| August | 76 | 465 | 76 | 465 |
| September | 70 | 455 | 71 | 456 |

**MDWTOWER**

| | Average Conditions | | Extreme Conditions | |
|---|---|---|---|---|
| Month | Wet Bulb Temperature (°F) | Outlet Water Temperature (°F) | Wet Bulb Temperature (°F) | Outlet Water Temperature (°F) |
| April | 52 | 89 | — | — |
| May | 55 | 89 | 62 | 91 |
| June | 68 | 92 | 70 | 93 |
| July | 71 | 93 | 73 | 94 |
| August | 70 | 93 | 71 | 93 |
| September | 63 | 91 | 65 | 92 |

Maximum Evaporation Rate (July) 2,070,000 $lb_m$/hr

**NDWTOWER**

| | Average Conditions | | | Extreme Conditions | | |
|---|---|---|---|---|---|---|
| Month | % Humidity | Air Temperature (°F) | Height (ft) | % Humidity | Air Temperature (°F) | Height (ft) |
| April | 68 | 54 | 244 | — | — | — |
| May | 70 | 65 | 249 | 72 | 68 | 189 |
| June | 72 | 74 | 246 | 74 | 76 | 222 |
| July | 73 | 77 | 245 | 77 | 78 | 245 |
| August | 73 | 76 | 254 | 77 | 76 | 233 |
| September | 70 | 69 | 256 | 75 | 71 | 215 |

Maximum Evaporation Rate (MAY) 2,290,000 $lb_m$/hr

**SPRACANL**

| | Average Conditions | | Extreme Conditions | |
|---|---|---|---|---|
| Month | Wet Bulb Temperature (°F) | Number of Passes | Wet Bulb Temperature (°F) | Number of Passes |
| April | 52 | 5 | — | — |
| May | 55 | 5 | 62 | 5 |
| June | 68 | 6 | 70 | 6 |
| July | 71 | 6 | 73 | 8 |
| August | 70 | 6 | 71 | 8 |
| September | 63 | 5 | 65 | 6 |

Maximum Evaporation Rate (May) 1,150,000 $lb_m$/hr

*Taken from Reference 2
DRYTOWER - Natural Draft Dry Cooling Tower
MDWTOWER - Mechanical Draft, Evaporative Cooling Tower
NDWTOWER - Natural Draft, Evaporative Cooling Tower
SPRACANAL - Spray Canal

16-45-18

III-C-119

# STRATEGIES FOR WASTE HEAT MANAGEMENT OF ONCE-THROUGH COOLING SYSTEMS

Ben L. Sill
Clemson University
Clemson, South Carolina 29631

## ABSTRACT

Many existing industrial plants use once-through cooling systems. It is thus useful to examine strategies which can help to minimize the impact of such thermal discharges without necessitating a switch to alternate cooling techniques. Near and far field situations are examined separately since different phenomena are dominant in each regime. In the near field, turbulent mixing with ambient fluid dominates as a means of energy redistribution while in the far field, energy is lost from the system through the surface, primarily by radiation and evaporation.

For the near field, volumes enclosed by specified isotherms are studied for both circular and slot jet discharges. The integral governing equations are solved in closed form with several simplifying assumptions. These solutions enable a straightforward examination of pertinent parameters as well as a comparative study of when each geometry is best.

Several distinct phases of the far field regime are discussed, again using the integral governing equations. First, the manner in which isotherm areas vary with plant cooling water flow is examined under the restriction that a fixed amount of heat is discharged. In this section, the question, "Is it more advantageous to discharge large quantities of warm water or a small amount of relatively hot water?" is answered. Next, it is assumed that the thermal discharge can either cool (through the free surface) somewhat before mixing with ambient fluid or alternatively be diluted some before it is allowed to cool. These two processes are compared with regard to the size of resultant isotherm areas. Thirdly, the amount of residual heat discharged from an impoundment is examined with regard to both the amount of reservoir flow-through as well as plant cooling water flow rate. Finally, plant operation necessary to meet specified surface isotherm area sizes is examined.

Closed form solutions are used throughout so that the relative magnitudes of various parameters and opposing effects can be readily examined. It is felt for the present purposes that any loss in detail is offset by a better understanding of basic strategies to help minimize the thermal impact of once-through cooling systems. Certainly the use of these ideas for design purposes would necessitate more detailed analysis.

## INTRODUCTION

The present work demonstrates that the manner in which thermal effluents are discharged can markedly affect resultant isotherm areas or volumes. It is the purpose of this study to provide some initial guidance as to strategies which will help minimize the thermal impact of once-through cooling systems. Near field situations are examined from the point of view of discharge geometry. Several important far field topics included are the effect of power plant output, condenser cooling water flow, dilution with ambient fluid, and energy passed downstream from an impoundment.

For the level of detail needed here, the integral governing equations are appropriate. For conservation of mass we have [1],

$$\frac{d}{dx}[\int_A \int \rho u dA] = e \qquad (1)$$

and for energy

$$\frac{d}{dx}[\int_A \int \rho C_v T U dA] = eC_v T_e + \int_P \int Q_n dP \qquad (2)$$

where x is the streamwise coordinate, $\rho$, U, $C_v$, and T the discharge density, velocity, specific heat, and temperature, respectively. Also, A is the cross sectional area of the discharge, e the entrainment rate of fluid (of temperature $T_e$) into the jet, and $Q_n$ is the heat flux through peripheral surface areas, P. In the very near field, momentum dominates buoyancy forces (densimetric Froude number is large), however, once the discharge reaches the surface, both momentum and buoyancy forces are small so that the momentum equation is needed only for the near field. It is written (for a stagnant ambient) as

$$\frac{d}{dx}[\int_A \int \rho U^2 dA] = 0 \qquad (3)$$

These three equations will be used to study thermal discharges in both the near and far field.

## NEAR FIELD

The near field region of a turbulent discharge is typically characterized by active turbulent mixing of the discharge stream with surrounding fluid as a result of velocity gradients generated by the jet. In this regime, little energy is lost from [illegible] system, instead, dilution through mixing redistributes the excess energy.

By assuming the jet velocity and temperature profiles are, respectively (with characteristic jet dimension b)

$$\frac{U}{U_m} = f(y/b) \tag{4}$$

and

$$\frac{T - T_e}{T_m - T_e} = j(y/b) \tag{5}$$

Equations (1) - (3) may be solved. In Equations (4) and (5), subscript m denotes centerline or maximum values (which may vary with x) and b is the local jet width (2 - D) or radius (axisymmetric), with y/b the non-dimensional position in the jet cross-plane. These equations apply for the fully developed portion of the jet downstream of the potential core region. Neglecting the thermal potential core, the volume of fluid contained by specified isotherms ($T_i$) becomes [2] (assuming a simple linear temperature profile, and $Q_n = 0$)

$$V_{2D} = \frac{LW^2}{4C_j}\left[\frac{M^4}{5} + \frac{4}{5M} - 1\right] \tag{6}$$

for a slot jet discharge of initial length L and width W. Also,

$$V_A = \frac{\pi b_o^3}{c_j}(M - 1)\left[M + \frac{1}{3}(M - 1)^2 - \frac{1}{M}\left\{2 + 3(M - 1) + 2(M - 1)^2 + \frac{1}{2}(M - 1)^3\right\} + \frac{1}{M^2}\left\{1 + 2(M - 1) + 2(M - 1)^2 + (M - 1)^3 + \frac{1}{5}(M - 1)^4\right\}\right] \tag{7}$$

for a circular discharge of initial radius $b_o$. Here $M = (T_d - T_e)/(T_i - T_e)$, $T_d$ is the discharge temperature, $C_j = db/dx$ usually taken as .22 [3]. Note that end mixing is neglected in obtaining Equation (6), so that it is not applicable for nearly square ports. However, since only ports with large aspect ratios will be compared anyway this does not present a problem. To a first order approximation, total isotherm volumes are obtained by adding the volume enclosed by the thermal core (which depends on the thermal core length) to Equations (6) and (7). These are [3]

$$(V_{2D})_P = \frac{5}{4}\frac{A_o^2}{L} \tag{8}$$

and

$$(V_A)_P = \frac{5}{3\sqrt{\pi}} A_o^{3/2} \tag{9}$$

for the two dimensional and axisymmetric geometries, respectively, with $A_o$ the area of the discharge port.

As a result, the ratio of total volumes becomes, assuming both ports have the same initial areas

$$\frac{V_A}{V_{2D}} = \frac{4}{\sqrt{\pi}} \; \frac{L}{A_o^{1/2}} \; \frac{(F_A + \frac{5}{3} C_j)}{(F_{2D} + 5C_j)} \tag{10}$$

with F the bracketed terms in Equations (6) and (7). When Equation (10) is less than one, an axisymmetric discharge produces a smaller volume for a specified isotherm than does a slot jet. When $V_A/V_{2D} > 1$, the converse is true. Note here (since buoyancy forces were neglected) that this type of analysis is applicable to chemical contaminants as well. For practical purposes, it is useful to relate the isotherm volume ratio to discharge flow rate. The electrical output of a power plant (P) may be related to the condenser cooling water flow $q_c$ and temperature rise ($\Delta T_c$) through the condensers as

$$P = Cq_c\Delta T_c \tag{11}$$

with C approximately .04 to .05 MW/cfs/°F for fossil fueled stations. Thus,

$$q_c = P/(C\Delta T_i M) \tag{12}$$

so that Equations (10) and (12) allow elimination of M, and the volume ratio can be plotted directly versus condenser cooling water flow. This has been done in Figure 1 for P = 500 MW, $\Delta T_i$ = 10°F and 5°F for various discharge areas (both slot and circular). Results from this crude analysis may be summarized in table form relating changes in independent variables to whether they favor the slot or axisymmetric jet. That is, Table I shows whether the range of $q_c$ (starting at zero) over which axisymmetric is preferable, increases or decreases. Overall, results from Figure 2 indicate that axisymmetric discharges are best at low condenser flows, and slot jet geometries best at high flows, and that doubling the discharge port area has much less effect than doubling the condenser cooling water flow rate.

## FAR FIELD

In the far field, velocity differences between the ambient and effluent streams are much less than in the near field so that turbulent mixing is typically very small. Thus, energy is lost in this region through the free surface, primarily due to radiation and evaporation. One dimensional analyses are commonly used to study far field isotherm areas and such an approach is employed below. Surface heat transfer is taken as the often used but simple form

$$Q_n = -k(T_s - E) \tag{13}$$

where $T_s$ is the local surface temperature, E an "equilibrium" temperature, and k the surface heat exchange coefficient. If slug velocity and temperature profiles are used ($f = j = 1$), Equation (2) may be solved directly for a stream of width w, depth d, and volume flow rate $q = Uwd$ to give [4]

$$\frac{T - E}{T_o - E} = \exp\left[-\int_0^x \frac{e}{\rho q}\,dx\right] \exp\left[-\int_0^x \frac{kw}{\rho C_v q}\,dx\right] \tag{14}$$

For examination of the far field, entrainment effects will be neglected ($e = 0$) so that the usual exponential decay form for temperature is obtained.

Since $(T_o - E)$ is the initial condition at $x = 0$, it is related to the temperature rise $(\Delta T_c)$ and flow $(q_c)$ through the condensers as

$$(T_o - E) = \Delta T_c \frac{q_c}{q_c + q_d} \tag{15}$$

where $q_d$ is water (at $T_d = E$) available for initial dilution of the discharge at $x = 0$ (or very small x compared with far field x values). The dilution D is defined as $D = 1 + q_d/q_c$ so that Equation (14) becomes (with surface area A),

$$\frac{\Delta T}{\Delta T_c} = \frac{1}{D} \exp\left[-\frac{kA}{\rho C_v q_c D}\right] \tag{16}$$

Isotherm Areas with Constant Heat Rejection

First it is instructive to determine how isotherm areas vary with condenser cooling water flow if a fixed amount of heat is rejected. Combining Equations (12) and (16) gives for surface area $A_i$ corresponding to isotherm $\Delta T_i$

$$\frac{A_i}{(\rho C_v P/kC\Delta T_i)} = -(\overline{q}_c + \overline{q}_d)\ln(\overline{q}_c + \overline{q}_d) \tag{17}$$

which is plotted in non-dimensional form in Figure 2 with $\overline{q} = q/(P/C\Delta T_i)$. This exercise yields the somewhat surprising result that for some situations, an increase in $q_c$ can either increase or decrease isotherm areas. In other words, if $(\overline{q}_c + \overline{q}_d) < 1/e = .368$, isotherm areas are decreased by decreasing either $\overline{q}$, whereas if $(\overline{q}_c + \overline{q}_d) > 1/e$, it is necessary to increase the flow rate (either $\overline{q}$) to realize an isotherm area reduction. Also, since the function is double valued, it means that discharge of a little "hot" water or a lot of warm water can give the same isotherm area. A third observation is that for $.25 \leq (\overline{q}_c + \overline{q}_d) \leq .5$ the resultant isotherm areas do not vary greatly. Thus in this range, fluctuations in plant operating characteristics (for constant P) would have little effect on the size of isotherm areas. The above results are summarized in Table II. These results indicate that a decrease in the size of isotherm areas can be obtained by altering the condenser cooling water flow $q_c$, or the dilution rate $q_d$. It is necessary, however, to know which side of the maximum (Figure 2) conditions lie so that the proper choice of either increasing or decreasing the flow rate can be made.

## Effect of Surface Cooling Before or After Dilution

A second alternative to examine is whether it is more advantageous to allow the effluent to cool before, or to cool after mixing with ambient fluid. For the case when a discharge is allowed to cool to $\Delta T_1$ before mixing with ambient fluid ($D_c$), Equation (16) is used to obtain

$$A_c = \frac{\rho C_v q_c}{k} \left[ \ell n \frac{\Delta T_c}{\Delta T_1} + D_c \ \ell n \frac{\Delta T_1}{D_c \Delta T_i} \right] \qquad (18)$$

which gives a minimum when $\Delta T_1 = D_c \Delta T_i$ with a resulting area of

$$(A_c)_{min} = \frac{\rho C_v q_c}{k} \ \ell n \frac{\Delta T_c}{D_c \Delta T_i} \qquad (19)$$

Equation (16) for instantaneous mixing before any cooling is allowed gives

$$A_i = \frac{\rho C_v q_c D_i}{k} \ \ell n \frac{\Delta T_c}{D_i \Delta T_i} \qquad (20)$$

so that

$$\frac{(A_c)_{min}}{A_i} = \frac{1}{D_i} \ \frac{\ell n \left( \frac{\Delta T_c}{D_c \Delta T_i} \right)}{\ell n \left( \frac{\Delta T_c}{D_i \Delta T_i} \right)} \qquad (21)$$

Note typically that $1 \leq D_i \leq D_c$ with the upper limit $D_i = D_c$ since in a particular situation we can assume that the same amount of fluid is available for mixing with either technique. Results for Equation (21) are presented in Figure 3, which shows that it is always advantageous to allow a thermal discharge to cool before any dilution is allowed. This is analogous to letting one's coffee cool before adding cream - a technique commonly used to hasten cooling. Additionally, we see from Figure 3 that the greater the dilution, the greater the advantage gained by cooling first.

## Excess Energy Discharged from Impoundments

A third topic of interest in the far field is to determine what percent of heat discharged to a cooling lake is passed downstream in the flow through the spillway. For most cooling ponds, a high percentage of the thermal energy discharged to the pond is dissipated to the atmosphere, and very little is passed downstream. Although this is the case, a small residual of heat remains in the water, which tends to warm the lake somewhat by raising its average temperature above the equilibrium value of E.

For a simple pond geometry, it is assumed that the heated water is discharged, mixes instantly with water at $\Delta T_i$ at a dilution D, and then cools over the total pond area $A_T$. Water is then withdrawn at a temperature rise of $\Delta T_i = T_i - E$, which corresponds to cooling over the total pond area. This water is heated by an increment $\Delta T_c$ as condenser cooling water and then discharged back into the lake at a flow rate of $q_c$. The process is continuous so long as the station is in operation. The assumption of intake water equal to $T_i$ was used in Reference [5] and is reasonable for deep stratified lakes. In such lakes, there is a large pool of relatively isothermal hypolimnetic water available to the intake.

The procedure used may be outlined as follows:

1. start with lake at temperature E
2. pump water through plant, raise temperature by $\Delta T_c$
3. discharge, mix, and cool to $\Delta T_i$
4. withdraw water at $\Delta T_i$ and add $\Delta T_c$ to it to obtain $\Delta T_d$
5. repeat steps 3 and 4 until a steady state discharge temperature rise is reached.

Equation (16) will be used with $A = A_T$ and $\beta_T$ written for the exponential term. The dilution D is defined as before, and $\Delta T_d$ is the discharge temperature rise above E after dilution. Mathematically, the above-outlined procedure becomes

| Step | | |
|---|---|---|
| 1 | $\Delta T_i\|_1 = \Delta T_d\|_1 \beta_T$ | $\Delta T_d\|_2 = \frac{\Delta T_c}{D} + \Delta T_i\|_1$ |
| 2 | $\Delta T_i\|_2 = \Delta T_d\|_2 \beta_T$ | $\Delta T_d\|_3 = \frac{\Delta T_c}{D} + \Delta T_i\|_2$ |
| ⋮ | | |
| n | $\Delta T_i\|_n = \Delta T_d\|_n \beta_T$ | $\Delta T_d\|_{n+1} = \frac{\Delta T_c}{D} + \Delta T_i\|_n$ |

Note here that the plant intakes at $\Delta T_i$ and the discharge mixes with water at $\Delta T_i$. Now with the fact that $\Delta T_d|_1 = \Delta T_c$, the above equations may be combined to give

$$[\Delta T_i]_n = \frac{\Delta T_c}{D} \beta_T [1 + (\beta_T) + (\beta_T)^2 + (\beta_T)^3 + \ldots + (\beta_T)^n] \qquad (22)$$

It is recognized that (since $\beta_T < 1$)

$$1 + \sum_{n=1}^{\infty} (\beta_T)^n = \frac{1}{1 - \beta_T} \qquad (23)$$

so that the steady state intake temperature rise is

$$\Delta T_i = \frac{\beta_T}{1 - \beta_T} \frac{\Delta T_c}{D} \qquad (24)$$

and the steady state discharge temperature rise is

$$\Delta T_d = \frac{\Delta T_c}{D} \frac{1}{1 - \beta_T} \qquad (25)$$

and also the temperature rise at the dam (located at an area equal to or less than the total lake area) is

$$\Delta T_{dam} = \Delta T_d \beta = \frac{\Delta T_c}{D} \frac{\beta}{1 - \beta_T} \qquad (26)$$

Now the excess energy released over the dam ($e_{dam}$) is given by

$$\%e_{dam} = \frac{C_v \Delta T_{dam} q_{dam}}{C_v \Delta T_c q_c} \times 100 \qquad (27)$$

which reduces to

$$\%e_{dam} = \frac{q_{dam}}{q_c} \left(\frac{1}{D}\right)\left(\frac{\beta}{1 - \beta_T}\right) \qquad (28)$$

Note here that $q_{dam}$ cannot exceed $Dq_c$ since this is the total amount of water affected by the plant. For greater values of $q_{dam}$, essentially no residual heat is contained in the excess discharge and thus there is no contribution to the excess energy discharged. For a typical cooling pond example, we take (assuming the dam is at the far end of the lake)

$A_T$ = 2000 acres
k = 6 BTU/hr/ft$^2$/$^o$F
$q_{dam}$ = 100 cfs
$q_c$ = 500 cfs

and %e is plotted in Figure 4. This plot points out that if the discharge were not diluted, a minimum of excess energy would be passed downstream. Also, for the higher dilution values, small differences in dilution do not appreciably effect the value of %e. It is also interesting to note that on a percentage basis (Equation (28)), the temperature rise of the condenser cooling water ($\Delta T_c$) does not enter the equation, only the condenser cooling water flow $q_c$ is important. Figure 4 thus shows that for a given lake discharge situation, the amount of excess energy passed downstream can be reduced if dilution of the plant discharge can be reduced. Thus, it is desirable to place the heated water into the lake in a manner which creates little or no mixing with ambient fluid.

As an extension of the above analysis, a cooling pond (where no dilution, only surface cooling occurs) can be placed between the plant and the cooling lake (where dilution is allowed). An exactly analogous procedure to that used in obtaining Equations (25) and (28) is used to obtain

$$\Delta T_d = \frac{\frac{\Delta T_c}{D}\beta_p}{1 - \beta_T\left(1 + \frac{\beta_p - 1}{D}\right)} \tag{29}$$

and

$$\%e_{dam} = \left(\frac{q_{dam}}{q_c}\right)\frac{1}{D}\,\frac{\beta\,\beta_p}{1 - \beta_T\left(1 + \frac{\beta_p - 1}{D}\right)} \tag{30}$$

In these expressions, $\beta_p$ is the exponential in Equation (16) with $A = A_p$ the pond area, and $D = 1$. For vanishingly small values of $A_p$, Equations (29) and (30) reduce to Equations (25) and (28) as would be expected. It can be shown by example that the use of an intermediate cooling pond reduces the percent of excess energy passed downstream.

## Plant Operation to Meet Surface Isotherm Area Restrictions

A final topic to examine is how to tailor power plant output to meet isotherm area restrictions. By combining Equations (11) and (16) we obtain as an expression for allowable output P which will meet an area limitation $A_i$ for isotherm $\Delta T_i$,

$$P = C\Delta T_i D q_c \exp\left[+\frac{kA_i}{\rho C_v D q_c}\right] \tag{31}$$

Note that if $\Delta T_i$ doubles, P doubles. This equation is plotted schematically in Figure 5 for P vs. D and the results show several interesting points. These are:

(1) Regardless of the value of D, there is a minimum value of P below which a plant will always meet the $\Delta T_i$, $A_i$ requirements. This $P_{min}$ is

$$P_{min} = \frac{CkA_i \Delta T_i}{\rho C_v} e$$

$$\text{at} \quad D_m = kA_i/\rho C_v q_c$$

(2) By either increasing or decreasing D from the value $D_m$, the allowable value of P can be increased.

(3) Largest allowable values of P are obtained at D = 1, and at very large D values with $P \propto D$ for $D >> 1$. Thus, if large quantities of water are available for dilution, then from the standpoint of maximum P, it pays to dilute as much as possible. However, if little dilution water is available, it is advantageous to dilute as little as possible to meet specific area requirements for a given isotherm value.

## SUMMARY

The preceding analyses demonstrate that much can be done to minimize or reduce the thermal impact of once-through cooling water discharges. Briefly some of the topics discussed above show that:

1. For the volume enclosed by higher valued isotherms (near field) either a slot or circular discharge can be most advantageous, depending on design criteria. Results indicate that for a given amount of heat rejection, axisymmetric discharges are better for the lower flow rates (higher $\Delta T$'s) and for large port areas. For other conditions, slot discharge geometries can be most advantageous.
2. When a fixed amount of heat is rejected, it is possible to obtain the same far field isotherm areas by rejecting a small amount of "hot" water or a relatively large amount of warm water. In certain cases, isotherm areas can be reduced by reducing dilution and/or condenser cooling water flows, in other situations these must be increased to decrease isotherm areas.
3. Isotherm areas may be reduced considerably by allowing the discharge to cool somewhat before mixing with ambient fluid.
4. Excess energy discharged from an impoundment can be reduced by decreasing dilution of the thermal discharge with ambient fluid, or by allowing the discharge to cool somewhat before mixing it with ambient fluid in the lake.

Table III presents some of the choices discussed above which are available to help tailor once-through cooling systems for particular far field requirements.

Certainly to use the above ideas for a design situation would require more detailed analysis, however, an attempt has been made to show that improvements can be made with once-through cooling systems before resorting to alternative cooling techniques.

## REFERENCES

1. Sill, B. L. and J. A. Schetz, "Thermal Pollution in a Bounded Waterway," in *Thermal Pollution Analysis*, Progress in Astronautics and Aeronautics, Vol. 36, M.I.T. Press, Cambridge, Massachusetts, 1975.

2. Sill, B. L. and A. Gnilka, "Optimum Discharge of Power Plant Cooling Waters," in *Thermal Pollution Analysis*, Progress in Astronautics and Aeronautics, Vol. 36, M.I.T. Press, Cambridge, Massachusetts, 1975.

3. Abramovich, G. N., *The Theory of Turbulent Jets*, The M.I.T. Press, Cambridge, Massachusetts, 1963.

4. Sill, B. L., "Heat Transfer and Evaporation from Open Water Bodies," Duke Power Company Technical Report, DUKE PWR/76-02, August 1976.

5. Ryan, P. J. and Harleman, D. R. F., "An Analytical and Experimental Study of Transient Cooling Pond Behavior," Ralph M. Parsons Laboratory, Dept. of Civil Engineering, Report No. 161, Massachusetts Institute of Technology, Cambridge, Massachusetts, January 1973.

## TABLE I

## EFFECT OF DESIGN PARAMETERS ON CIRCULAR AND SLOT JETS

| Independent Variable | Geometry Favored |
|---|---|
| smaller flow rates | axisymmetric |
| increase port area | axisymmetric |
| increase $\Delta T_i$ | slot |
| increase L (constant port area) | slot |

## TABLE II

## EFFECT OF CONDENSER COOLING WATER (CCW) AND DILUTION FLOW ON ISOTHERM AREAS

| Total Flow $(\bar{q}_c + \bar{q}_d)$ | $A_i$ Isotherm Areas |
|---|---|
| $(\bar{q}_c + \bar{q}_d) < .368$ | dec. w/dec. $\bar{q}_c + \bar{q}_d$ |
| $(\bar{q}_c + \bar{q}_d) > .368$ | dec. w/inc. $\bar{q}_c + \bar{q}_d$ |
| $.25 \leq (\bar{q}_c + \bar{q}_d) \leq .5$ | approx. constant |

## TABLE III

## SUMMARY OF FAR FIELD EFFECTS WITH FIXED HEAT REJECTION

| Control | Effect on Isotherm Areas | Effect on Energy Passed Downstream |
|---|---|---|
| increase CCW flow | increase or decrease | slight increase |
| decrease CCW flow | increase or decrease | slight decrease |
| increase dilution | increase or decrease | increase |
| decrease dilution | increase or decrease | decrease |
| cool before diluting | decrease | decrease |

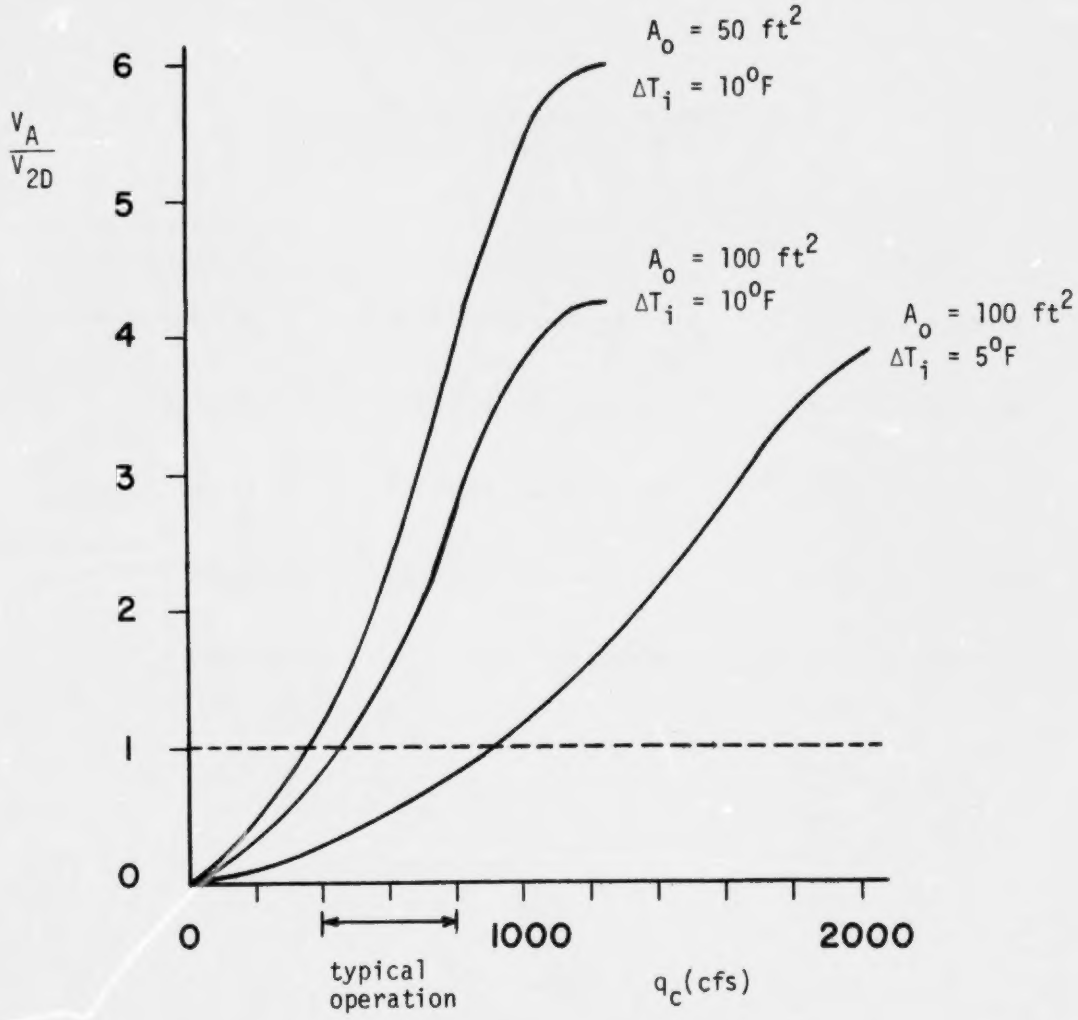


Figure 1. Comparison of Near Field Volumes Enclosed by Axisymmetric and Slot Discharges for a 500 MW Plant (with L = 25 ft).

3424

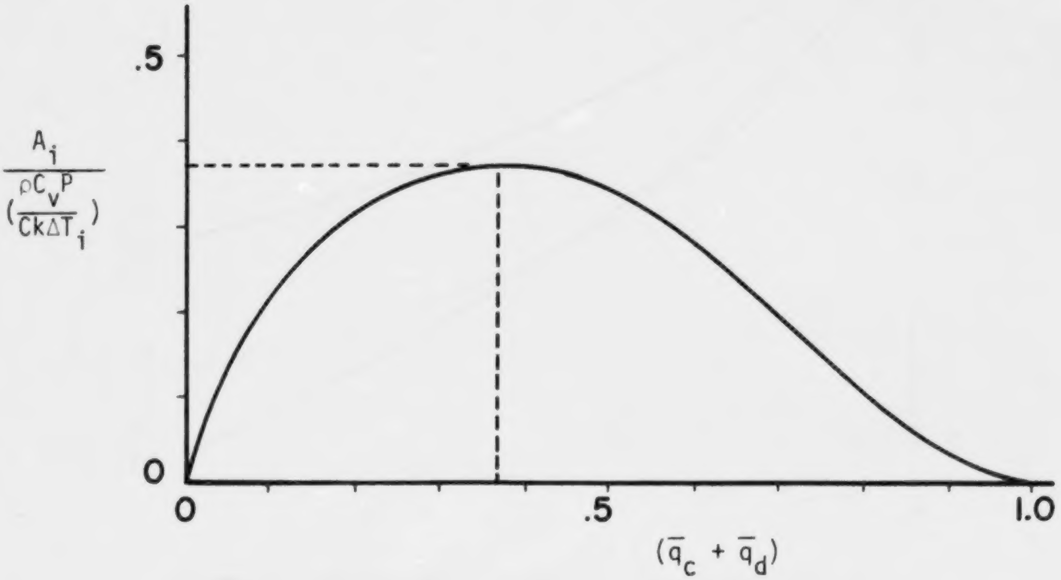


Figure 2. Isotherm Area as a Function of Condenser and Dilution Flows.

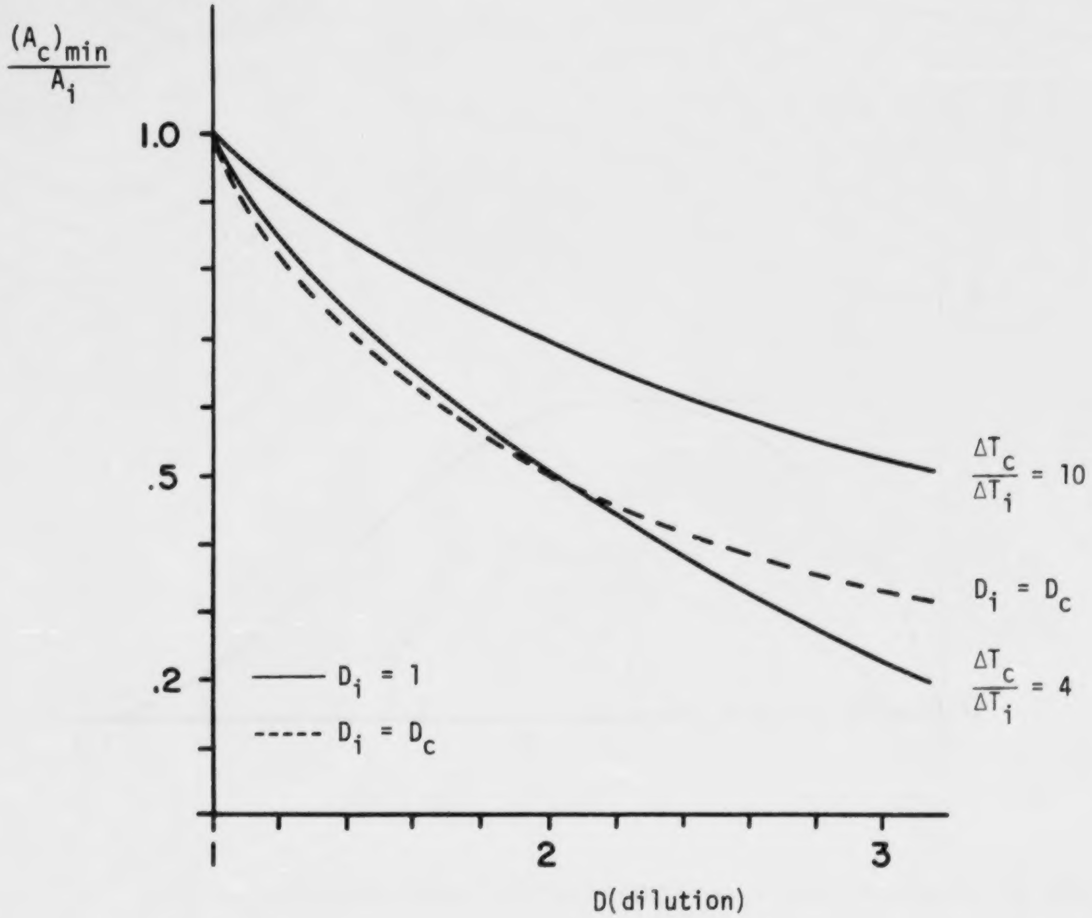


Figure 3. Reduction in Isotherm Areas Gained by Cooling Before Mixing as Opposed to Mixing Before Cooling.

344<

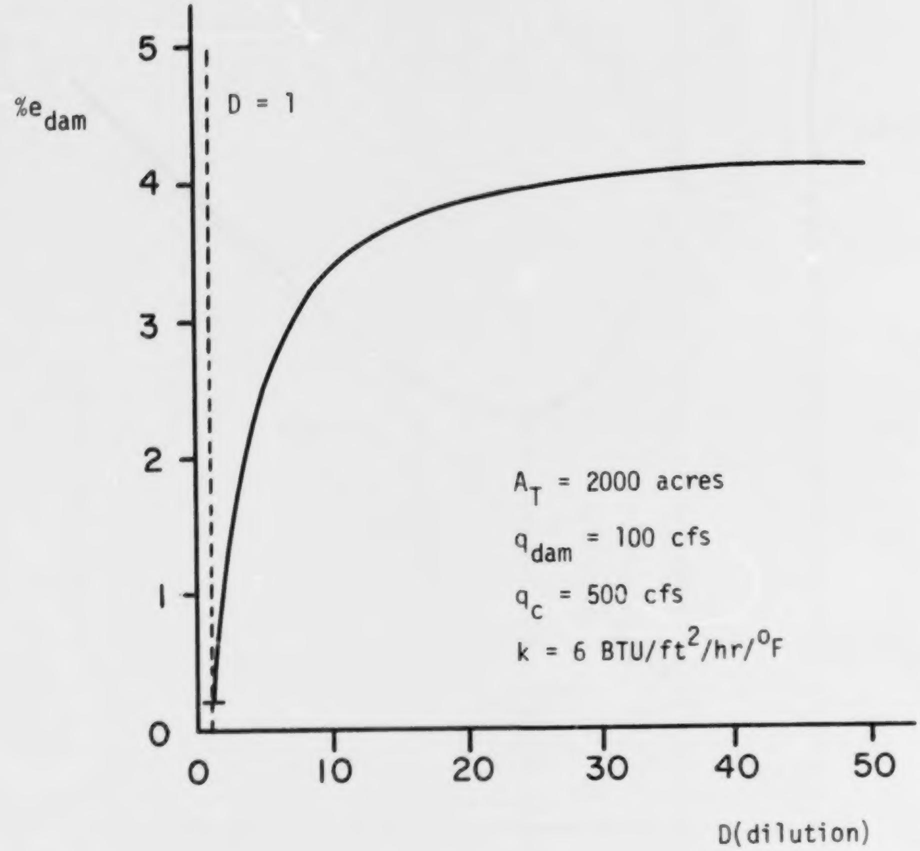


Figure 4. Example of the Effect of Dilution on the Excess Energy Discharged from an Impoundment.

345<

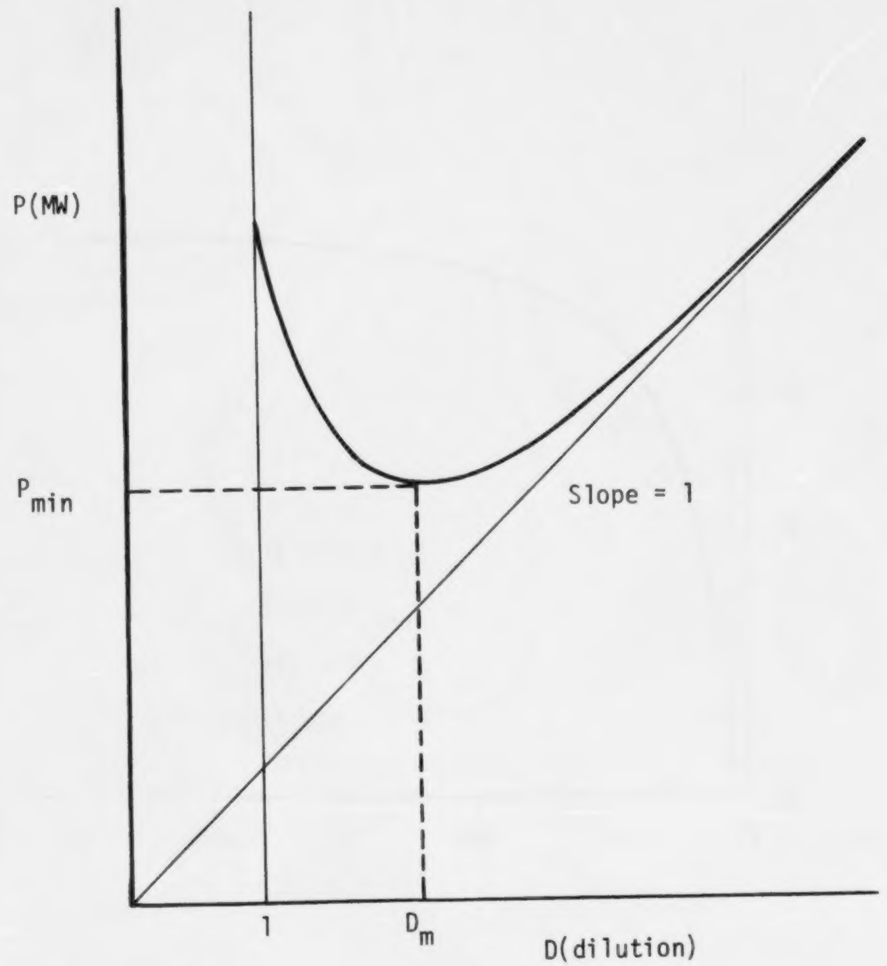


Figure 5. Effect of Dilution of Allowable Plant Output to Meet Specified $A_i$, $\Delta T_i$ Restrictions.

17-45-19

# THERMAL IMPACT REDUCTION BY DILUTION
# BIG BEND STATION, TAMPA, FLORIDA

William J. Johnson, Ph.D., P.E.
Tampa Electric Company
Tampa, Florida U.S.A.

## ABSTRACT

The paper describes the design and performance of a dilution pumping system installed with the second generating unit at Big Bend Station and first operated in April, 1973. Also described are the modifications incorporated to allow the addition of the third generating unit in May, 1976. The results of mathematical modeling of the plant's thermal effects are presented along with documentation of post-operational conditions by aerial infrared imagery.

The effects of input from environmental regulatory agencies on the system's design are reviewed. Actions by the Environmental Protection Agency in response to the company's application to discharge under alternative and less stringent effluent limitation filed pursuant to Section 316(a) of Federal Water Pollution Control Act Amendments of 1972 are reviewed. A description of the Section 316 biological studies, which were undertaken in support of the application, and interim findings were presented.

## INTRODUCTION

The Federal Water Pollution Control Act Amendments of 1972 and EPA's subsequent interpretations and implementation are the most significant federal actions affecting the electric utility industry's use of water. Section 304(b) of the Act required the EPA Administrator to publish regulations providing guidelines for effluent limitations setting forth the degree of effluent reduction attainable through the application of the best practicable control technology currently available (BPCTCA).

For the thermal component of a plant's discharge BPCTCA has been defined as close cycle cooling. Section 316(a) of the Act provides that whenever the owner or operator of any point source can demonstrate to the satisfaction of the Administrator the limitation proposed for the control of the thermal component of any discharge will require more stringent control measures than are necessary the Administrator may impose less stringent limitations. A comprehensive biological assessment of the receiving water body, which has become known as the "316 Demonstration", is required to demonstrate no significant impact.

The complexity of these regulations are probably the greatest for existing plants especially those that were under development during the formative years of federal regulation. During this period it was unclear among the federal, state and local agencies as to the jurisdiction in power plant permitting. Certainly the states have always maintained authority but with the growing momentum of "environmentalist" interaction, the utility seeking a "permit to construct" found itself attempting to fulfill requirements of "unallied" agencies which were not in conformity with one another.

Many companies nationwide have been living through such a period. The end result has been power plants utilizing a variety of condenser cooling technology, none of which may be the optimum engineering design but all of which reflect an ever-changing regulatory mechanism.

The following paragraphs describe cooling systems employed (or nearly so) at Big Bend Station as well as some of the surrounding events which led to their selection.

## SYSTEM DESCRIPTIONS

### Plant Generating Units

Big Bend Station is located 10 miles south of the City of Tampa, Hillsborough County, Florida, on the easterly shore of Hillsborough Bay which is a northeasterly extension of Tampa Bay. Located just north of Big Bend Road, the site is approximately 1 mile west of U.S. Highway 41. Figure 1 shows the site location and its contiguous areas.

The three generating units are essentially identical each rated at 445 MW nameplate. For design purposes this is considered the maximum thermal output. In reality the planned normal maximum dispatch output will be 400 MW gross. Pertinent data relevant to the cooling water system is as follows:

| | |
|---|---|
| Heat Rejection Rate: | 2 X $10^9$ BTU/Hr. |
| Circulating Water Flow: | 537 cfs |
| Condenser Temperature Rise: | 16.8°F (100% F.L.) |

Each unit is serviced by two half-size pumps arranged with dual flow screens as shown in Figure 2. The screen is termed "an environmentally promising alternative" in EPA's "Development Document for Best Technology Available for the Location, Design, Construction and Capacity of Cooling Water Intake Structures for Minimizing Adverse Environmental Impact."[1] This is considered so because there is no confining concrete structure which might trap fish. The screen hangs from a platform and is surrounded by water on all sides. The screen approach velocity based on total screen frontal area is 1.45 fps. The actual net velocity through the screen openings is 1.93 fps.

The cooling water upon exiting a split single pass condenser is discharged to a common discharge channel through a discharge structure shown in Figure 3. This structure is arranged with baffles to reduce velocity erosion of the far channel bank. The retention time of the circulating water subsequent to increase in temperature, i.e., from the condenser inlet to leaving the discharge structure, is approximately 1.5 minutes for each unit. The maximum velocity within the system is 9.5 fps.

## Original Dilution System Installation (To Serve Units 1 & 2)

Unit 1 was permitted in 1969 just as the State of Florida began to consider the thermal effects of power plant cooling water discharges on receiving water bodies. The only requirement imposed was that biological studies be executed. These studies by comparison with modern day "316 Demonstration" studies were minor.

The dilution concept was first employed to service Units 1 & 2 in response to pressures brought by the state regulatory agency. In 1971 and 1972 when construction permits were being sought the agency required that "some thermal control technology be utilized". The system shown in Figure 4 was selected from among a variety of arrangements and proposed to and accepted by the agency. It was designed to accommodate ten dilution pumps of the type as shown in Figure 5. The dilution pump supplies 890 cfs of ambient temperature bay water to the dilution channel. The pump structure is provided with trash racks to remove any large floating debris. The low-speed (58 rpm) and large-clearance design of the pump (would pass a 12-inch sphere) permits fish to pass safely. The combined discharge of Units 1, 2 and 3 and the thermal dilution system totals 2501 cfs. The thermal dilution system effectively reduces the temperature rise of the combined discharge at full-load conditions from 16.8°F to a mixed temperature rise of 10.8°F. The total discharge flows west within a discharge channel to be returned to Hillsborough Bay. This project included a second pump as 100% back-up.

Prior to completion of Unit 2 and the start-up of the dilution system the Environmental Protection Agency acquired authority over discharges to "navigable waters" through the 1899 Refuse Act which had been briefly administered by the U.S. Army Corps of Engineers. EPA stated that ". . only because the dilution system was virtually complete and also that it had been approved by the state agency would it be allowed to operate". Additionally, the agency stated "under no circumstances would the dilution concept be approved for future units".

## Modifications to Dilution System (To Serve Units 1-3)

Permitting activities for Unit No. 3, to be operational in 1975, commenced in 1972. Based upon EPA's stated position closed cycle cooling alternatives were evaluated but only after long consideration of challenging the agency. Debate was sufficiently long that a condenser optimized for once-through cooling was purchased. Concern for the construction schedule and the potential delays of such a challenge finally solidified the company's decision to "go" closed-loop cooling. After an analysis of all available alternatives a spray cooling canal was selected.

During this same time the Federal Water Pollution Control Act Amendments of 1972 became law (PL 92-500) and EPA took on the challenge of implementation.[2] In late 1974 construction was approximately 60% complete on the unit and the closed spray cooling canal when the implications and opportunities under Section 316 of the Act became known. The decision was made to approach the agency with a proposal containing alternative expansions of the dilution system including up to 6 dilution pumps. It was hoped that some larger dilution pumping capacity would reduce temperatures sufficiently to satisfy the agency. The proposal was coupled to a "316 Demonstration" patterned after EPA Region IV guidelines.[3]

A round of meetings commenced in early 1975 with the agency being receptive to the company's proposal. The EPA expressed several concerns (1) the volume of dilution water and associated entrainment problems and (2) the thermal impact on the shallow embayment south of the plant into which the mixture would be discharged. In a surprising counterproposal the agency asked the company to consider (a) no expansion of dilution beyond the one existing pump and (b) removal of the existing pump from service returning the entire plant to the once-through mode. EPA pointed out that they felt the bay could receive the once-through discharge without significant impact. This opinion was based upon their analysis of the 5 years of biological data which existed. At this point all activities on the closed spray cooling system were terminated.

350<

It was mutually agreed that a "Pre-316 Hearing" would be held before both the EPA and the Florida Department of Environmental Regulation. The company would present all cooling alternatives considered while the regulatory agencies and public would offer comment. This hearing took place in August, 1975 with the approval for counterproposal (a) as shown in Figure 6.

Also approved as integral part of the cooling water system was a breakwater extension intended specifically to control recirculation. As a result of regulatory agency concern over a dredged earthen fill extension, the breakwater was constructed of concrete T-beams salvaged from a nearby bridge being demolished. The breakwater was formed by inverting the T's and laying four edge to edge as a base and creating a pyramid stack. A fabric filter was placed under the first layer to stabilize the foundation sand.

Construction commenced in December, 1975 after securing permits from state and federal agencies. The unit and the dilution system were operating commercially May 1, 1976.

The discharge water flows and their temperatures are presented in the following table. It is assumed that all three units are simultaneously at full load. Average load temperature rises are also given:

| | Unit 1 | Unit 2 | Unit 3 |
|---|---|---|---|
| Unit flow, cfs | 537 | 537 | 537 |
| Cumulative flow | 537 | 1074 | 1611 |
| Unit dilution flow | - | 890 | - |
| Total flow | 537 | 1964 | 2501 |
| Max. cumulative temp. rise after dilution | 16.8 | 9.2 | 10.8 |
| Avg. cumulative temp. rise after dilution | 11.0 | 6.0 | 7.0 |

From all the findings available thus far, it appears that a fourth generating unit could be added to the system with only the operation of the second existing dilution pump while reasonably anticipating no adverse environmental effects.

## MATHEMATICAL MODEL

Hydrothermal modeling was carried out to provide a predictive tool which would fulfill the anticipated desires of the regulatory agencies.

The mathematical model considered buoyancy effects, energy losses, entrainment of underlying cold water into the surface flow, and heat loss to the atmosphere. Two different models were used, one for the discharge channel which assumes a two-layer flow through a rectangular cross-section and one for the bay which assumes a two-layer radial flow. The following assumptions were made:

1. Slack tide condition
2. Rectangular open channel two-layer flow in the discharge channel
3. Radial flow into Hillsborough Bay
4. Steady state source flow
5. Constant shearing stress factor

The basic equations expressing hydrostatic pressure, momentum in the X-direction, mass conservation, and heat conservation for both layers were integrated and transformed to the solvable forms which only depend on the first order partial derivative of X in the rectangular channel flow and r in the radial flow.

For rectangular channel flow:

$$\frac{\partial u_1{}^2 h_1}{\partial x} = \frac{h_1{}^2}{2} \frac{\partial g'}{\partial x} - h_1 g \frac{\partial H}{\partial x} - \frac{\tau_i}{\rho} \qquad (1)$$

$$\frac{\partial u_2{}^2 h_2}{\partial x} = h_1 h_2 \frac{\partial g'}{\partial x} - h_2 g \frac{\partial H}{\partial x} + \frac{\tau_i}{\rho} - \frac{\tau_o}{\rho} \qquad (2)$$

$$\frac{\partial u_1 h_1}{\partial x} = - \frac{\partial u_2 h_2}{\partial x} = U_e \qquad (3)$$

$$h_1 + h_2 = H \qquad (4)$$

$$\rho c_p \frac{\partial(\Delta T u_1 h_1)}{\partial x} = - K \Delta T \qquad (5)$$

and for radial flows:

$$\frac{1}{r} \frac{\partial u_1{}^2 h_1 r}{\partial r} = \frac{h_1{}^2}{2} \frac{\partial g'}{\partial r} - h_1 g \frac{\partial H}{\partial r} - \frac{\tau_i}{\rho} \qquad (6)$$

$$\frac{1}{r} \frac{\partial u_2{}^2 h_2 r}{\partial r} = h_1 h_2 \frac{\partial g'}{\partial r} - h_2 g \frac{\partial H}{\partial r} + \frac{\tau_i}{\rho} - \frac{\tau_o}{\rho} \qquad (7)$$

$$\frac{1}{r}\ \frac{\partial u_1 h_1 r}{\partial r} = -\frac{1}{r}\ \frac{\partial u_2 h_2 r}{\partial r} = U_e \qquad (8)$$

$$h_1 + h_2 = H \qquad (9)$$

$$\rho c_p\ \frac{1}{r}\ \frac{\partial(\Delta T u_1 h_1 r)}{\partial r} = -K\Delta T \qquad (10)$$

where subscripts 1 and 2 refer to the upper and lower layers:

$H = h_1 + h_2$ = total depth

$\tau_i$ = interfacial shearing stress

$\tau_o$ = bottom shearing stress

$U_e$ = rate of entrainment from colder layer to warmer layer

K = heat transfer coefficient

$g' = g\,\frac{\Delta\rho}{\rho}$ = desimetric gravitational acceleration

Equations (1) to (5) and (6) to (10) are solved simultaneously for $u_1$, $h_1$, $\Delta T$, $\rho$, $u_2$ and $h_2$ by method of finite difference.

In the discharge channel, the above parameters are solved for points between the initial critical flow section and the outlet to the bay. This then defines initial conditions for determining the flow pattern into Hillsborough Bay.

The rate of entrainment, $U_e$, is determined from the curve of Lean and Willock which has the form of:

$$U_e = 0.0025\ F^4\ u \qquad (11)$$

Equation (11) is valid in the range of Froude Number, F., between 1.3 and 0.32.

Equations (5) and (10) are solved independently after the parameters $U_1$, $h_1$, and T are known at finite intervals. This can be expressed as:

$$T_x - E = (T_o - E)\ \exp\left(\frac{-K\Delta X}{\rho C_p U_1 h_1}\right) \qquad (12)$$

for rectangular channel and

$$T_r - E = (T_o - E) \exp\left(- \frac{K\Delta A}{\rho C_p Q}\right) \qquad (13)$$

for radial flow where:

$T_o$ = Temperature of water entering increment

E = Equilibrium temperature

$T_x$, $T_r$ = Temperature of water at end of increment

$\Delta X$ = Length of the increment

$\rho$ = Density of the upper warm layer

$U_1$ = Velocity in the upper warm layer

$C_p$ = Specific heat of water at constant pressure

$h_1$ = Thickness of the upper warm layer

$\Delta A$ = Surface area of the increment

Q = Accumulated flow rate

The solution of equations (1) to (5) and (6) to (10) yield input to equations (12) and (13) which finally yield the decay of temperature in the discharge channel and in Hillsborough Bay.

The mathematical model was used to predict the thermal effect of operating Units 1, 2 and 3 at 100 percent and average 64 percent of full load. The results are presented in Figures 7 and 8. These results were transformed to isothermal contour maps as presented in Figures 9 and 10.

Thermal plume studies discussed in the next section which approximated assumed conditions of the mathematical model were modeled to examine agreement. For those conditions good correlation was found.

## AERIAL INFRARED IMAGERY SURVEYS

The company has employed aerial infrared imagery techniques since 1969 to define, at least in a qualitative sense, the extent of the thermal plume. Four such surveys were executed in the period through 1974, three of which were coupled with an extensive ground truthing effort. Two of these three also included photo-tracing of current tracking drogues.

In 1975 and 1976, the EPA commenced a program of thermal plume surveillance by aerial infrared imagery. This service is provided to the EPA regional offices by their Environmental Monitoring and Support Laboratory in Las Vegas, Nevada. Big Bend Station was flown on September 16, 1975 and again on October 15, 1976.

## 1975 Survey

This survey observed the effects of Units 1 and 2 operating with the original dilution system installation (see Figure 4). The following coverages were accomplished: (a) low tide stage; (b) mid-flood tide stage; (c) high tide stage; (d) mid ebb tide stage. The black and white imagery is shown in Figure 11. The average plant load factor for the period beginning at 12 midnight through 12 noon was 60% and ranged from 49% to 73% of full load. Ground truth water surface temperatures were acquired at select points over the survey area.

In a qualitative sense, at least, the following observations or interpretations may be made: (1) the heating of the embayment south of plant through which the diluted mixture flowed and which was of concern to the EPA is evident; (2) no evidence of flushing of warm water as tide ebbs, demonstrating absence of stratification; (3) recirculation effects are evident (Figure 11); (4) the approximation of radial flow conditions during slack water (Figure 11); and (5) the relatively cold bottom water introduced by the dilution pumps is especially evident at maximum surface water temperatures (Figure 11).

## 1976 Survey

This survey observed the effects of Units 1-3 operating with the modified dilution system (see Figure 6). The following coverages were accomplished: (a) high tide stage; (b) early ebb tide stage; and (c) late ebb tide stage. It was intended to accomplish the same coverages as in the 1975 survey, however, mechanical problems forced abortion of the flight program. This imagery is shown in Figure 12. The average plant load factor for the period beginning 12 midnight through 12 noon was 64.1% and ranged from 51% to 81% of full load.

Ground truth water surface temperatures were acquired at select points over the survey area. In addition, a continuous record of discharge temperature after dilution is provided by a three-by-three grid of sensors located about 200 feet west of the dilution pumps. This system provides temperature data on a routine basis to fulfill permit requirements.

In a similar fashion certain important qualitative interpretations may be made. They are: (1) the radial flow as assumed in the model is again seen to exist during slack water (Figure 12a); (2) the effective elimination of recirculation by the extended breakwater though some leakage is evident (Figure 12a, b, c); (3) the warm surface layer in the embayment south of the plant indicating warm discharge water being carried in on flooding tide (Figure 12a); and (4) the rapid return to natural ambient temperatures of surface water in the embayment suggesting stratified conditions and a very shallow warm surface layer (Figures 12b, c).

## SUPPORTING STUDIES

Ecological studies have been conducted in the area of the Big Bend Station since April, 1970, seven months prior to the start up of Unit No. 1. Since that time, the numbers and types of parameters measured and methodologies utilized have varied but the ultimate goal has always been to ascertain the effects of the cooling water system on populations of local marine organisms. Increases in water temperature can influence numerous biological functions and the physiochemical stability of the water itself. Either of these factors, acting independently or synergistically may result in stress and/or death to aquatic organisms. Past studies are published in 20 quarterly and 5 annual reports.

This data was sufficiently complete to allow EPA to make an independent judgement that the dilution system at this location could protect and allow the propogation of a balanced indigenous population of marine organisms. They look toward a "316 Demonstration" as the final test of this judgement.

Studies were proposed with the goal being a conclusive determination (within the scope of a 316 Demonstration) of any effects to the aquatic environs at Big Bend Station that can be related to thermal effluent. The studies were designed in accordance with EPA Region IV's guidelines and specifications. The study would document:

(1) The condition of basic chemical and physical water quality parameters.

(2) The effects on finfish and shellfish of intake structure impingement.

(3) The numbers and kinds of fish eggs and larvae entrained and viable after entrainment.

(4) The numbers and kinds of phytoplankton in source and receiving waters.

(5) Populations of fish and invertebrates in receiving and control water bodies.

(6) Populations of benthic organisms in thermal and control areas.

The data collection program to support these analyses covered 15 months between January 1, 1976 and March 31, 1977. Three months were prior to the operation of Unit No. 3 with the modified dilution system. The final report will be submitted to EPA in September, 1977.

Tentative findings show that a balanced indigenous population of marine organisms is being maintained.

## CONCLUSIONS

Results of extensive monitoring and testing and economic and energy considerations support the conclusion that thermal impact reduction by dilution appears to be an appropriate thermal control system at this location.

The "316 Demonstration" has tentatively concluded that a "balanced indigenous population of fish, shellfish and wildlife" is being maintained.

From all the findings thus far it appears that a fourth generating unit could be added to the system with only the operation of the second existing dilution pump while reasonably anticipating no adverse environmental effects.

It was estimated that on an annual basis the operating and maintenance cost differential between the dilution system and the spray cooling system is $1.1 million (1976).

## ACKNOWLEDGEMENT

In memorium, I would like to acknowledge the fine contribution of Mr. Norman Smith to the engineering of this project and to the science of thermal modeling. Taken early in his years, he shall be remembered and greatly missed by his friends and associates.

## REFERENCES

(1) "Development Document for Best Technology Available for the Location, Design, Construction and Capacity of Cooling Water Intake Structures for Minimizing Adverse Environmental Impact", Effluent Guidelines Division, Office of Water and Hazardous Materials, U.S. Environmental Protection Agency, Washington, D.C., 20460, April, 1976.

(2) "Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Steam Electric Power Generating Point Source Category", Effluent Guidelines Division, Office of Water and Hazardous Materials, U.S. Environmental Protection Agency, Washington, D.C. 20460, October, 1974.

(3) "Basic Guide to the Design of 316 Demonstrations", U.S. Environmental Protection Agency, Region IV, Atlanta, Georgia 30308, August, 1974.

358<

WJJ

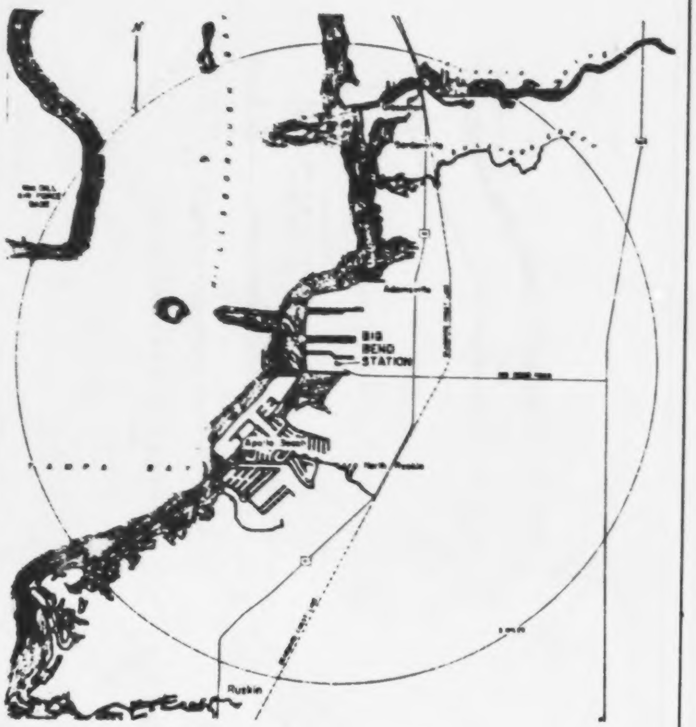

N
BIG
BEND
STATION
TAMPA BAY
Apollo Beach
North Ruskin
Ruskin

FIGURE 1 LOCATION MAP BIG BEND STATION

Big Bend Station
Tampa Electric Company

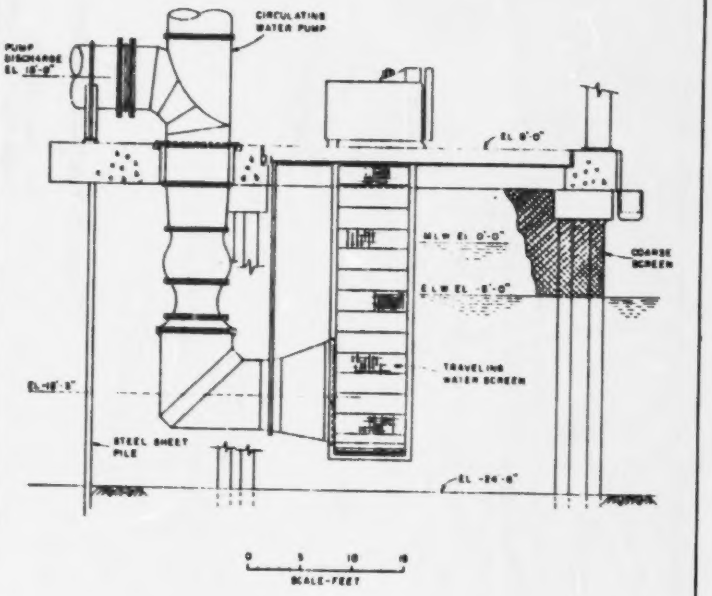

CIRCULATING WATER PUMP
PUMP DISCHARGE EL 18'-0"
EL 9'-0"
MLW EL 0'-0"
ELW EL -8'-0"
COARSE SCREEN
TRAVELING WATER SCREEN
EL -18'-3"
STEEL SHEET PILE
EL -24'-0"
0
5
10
15
SCALE-FEET

FIGURE 2 CIRCULATING WATER INTAKE

Big Bend Station
Tampa Electric Company

359<

13

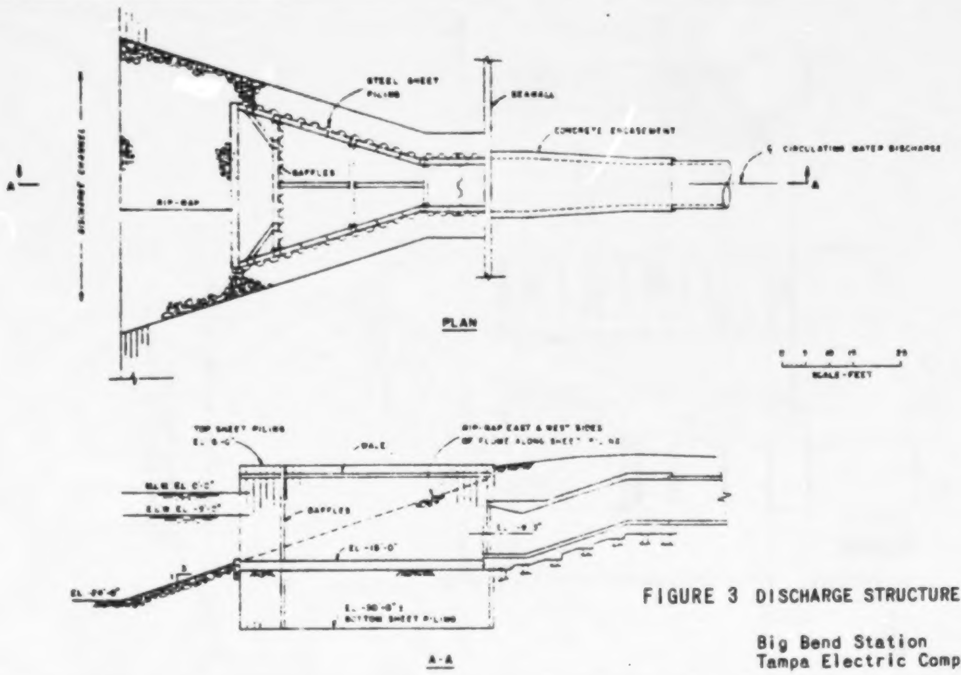

STEEL SHEET PILING
SEAWALL
CONCRETE ENCASEMENT
℄ CIRCULATION WATER DISCHARGE
DISCHARGE CHANNEL
BAFFLES
RIP-RAP
A
A
PLAN
0 5 10 15 20
SCALE-FEET
TOP SHEET PILING EL. 8'-0"
WALE
RIP-RAP EAST & WEST SIDES OF FLUME ALONG SHEET PILING
BAFFLES
EL. -15'-0"
EL. -30'-0" ± BOTTOM SHEET PILING
A-A

FIGURE 3 DISCHARGE STRUCTURE

Big Bend Station
Tampa Electric Company

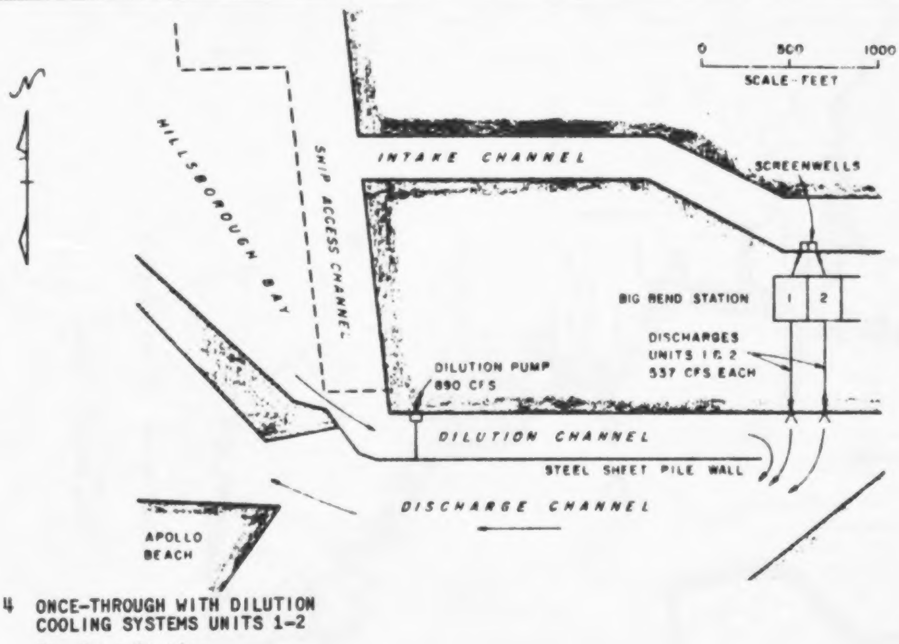

N
0 500 1000
SCALE-FEET
HILLSBOROUGH BAY
SHIP ACCESS CHANNEL
INTAKE CHANNEL
SCREENWELLS
BIG BEND STATION
1
2
DISCHARGES UNITS 1 & 2 537 CFS EACH
DILUTION PUMP 890 CFS
DILUTION CHANNEL
STEEL SHEET PILE WALL
DISCHARGE CHANNEL
APOLLO BEACH

FIGURE 4 ONCE-THROUGH WITH DILUTION COOLING SYSTEMS UNITS 1-2

Big Bend Station
Tampa Electric Company

360

14

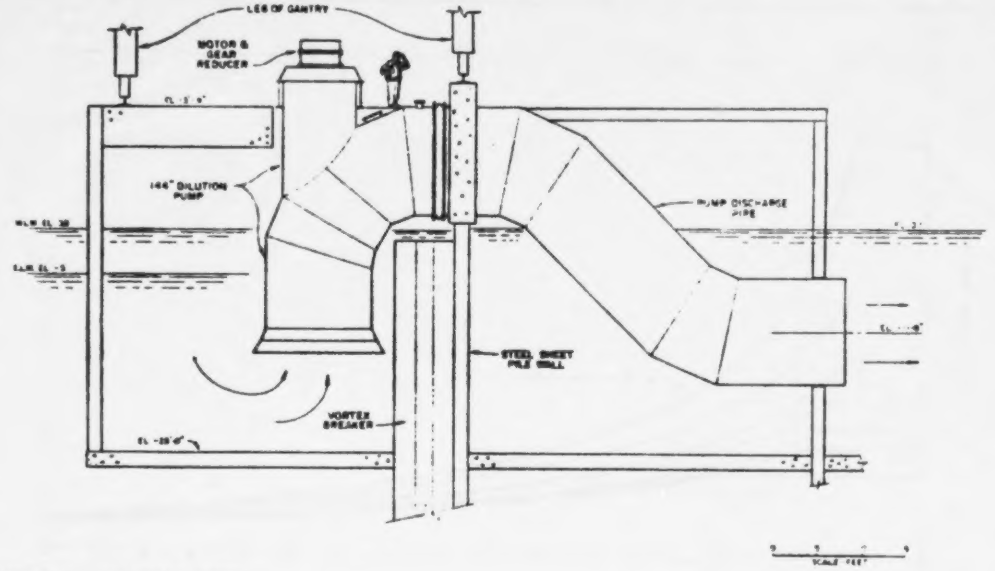

LEG OF GANTRY
MOTOR & GEAR REDUCER
EL -3'-9"
144" DILUTION PUMP
PUMP DISCHARGE PIPE
MLW EL 30
ELW EL -5
STEEL SHEET PILE WALL
VORTEX BREAKER
EL -28'-0"
SCALE-FEET

FIGURE 5 DILUTION PUMP

Big Bend Station
Tampa Electric Company

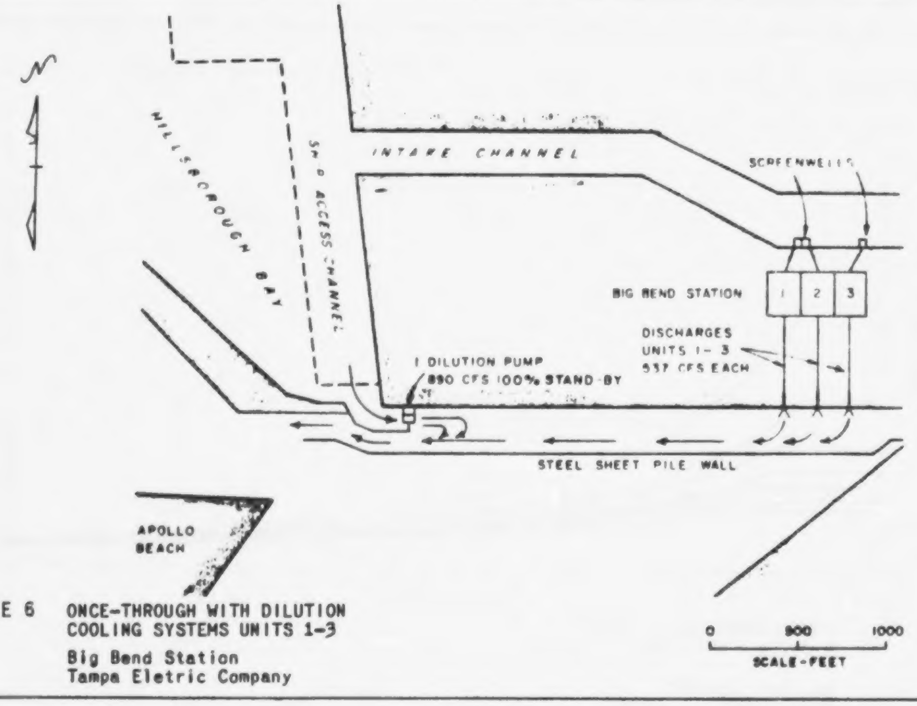

N
HILLSBOROUGH BAY
SHIP ACCESS CHANNEL
INTAKE CHANNEL
SCREENWELLS
BIG BEND STATION
1
2
3
DISCHARGES
UNITS 1 - 3
537 CFS EACH
1 DILUTION PUMP
890 CFS 100% STAND-BY
STEEL SHEET PILE WALL
APOLLO BEACH
0
500
1000
SCALE-FEET

FIGURE 6 ONCE-THROUGH WITH DILUTION
COOLING SYSTEMS UNITS 1-3

Big Bend Station
Tampa Eletric Company

361<

15

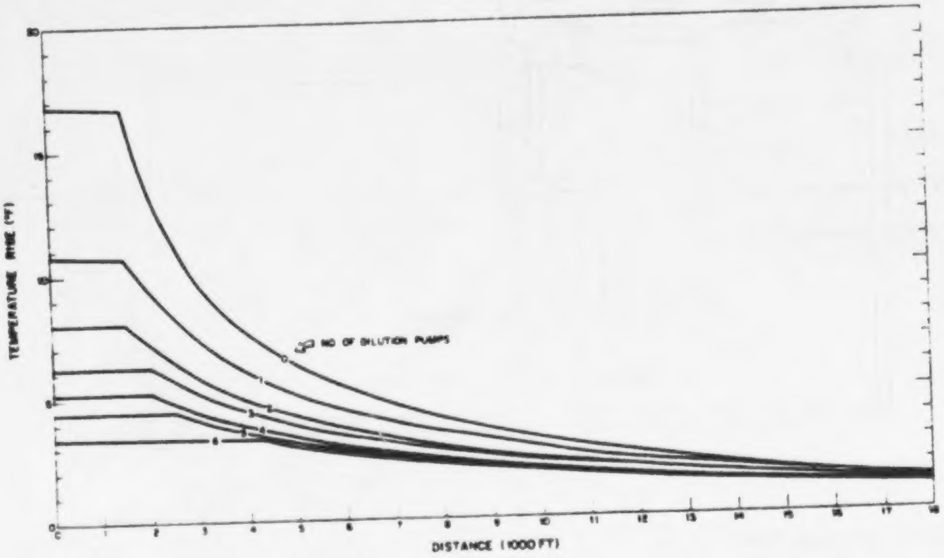


FIGURE 7 TEMPERATURE DECAY CURVES
3 UNITS - 100% LOAD

Big Bend Station
Tampa Electric Company

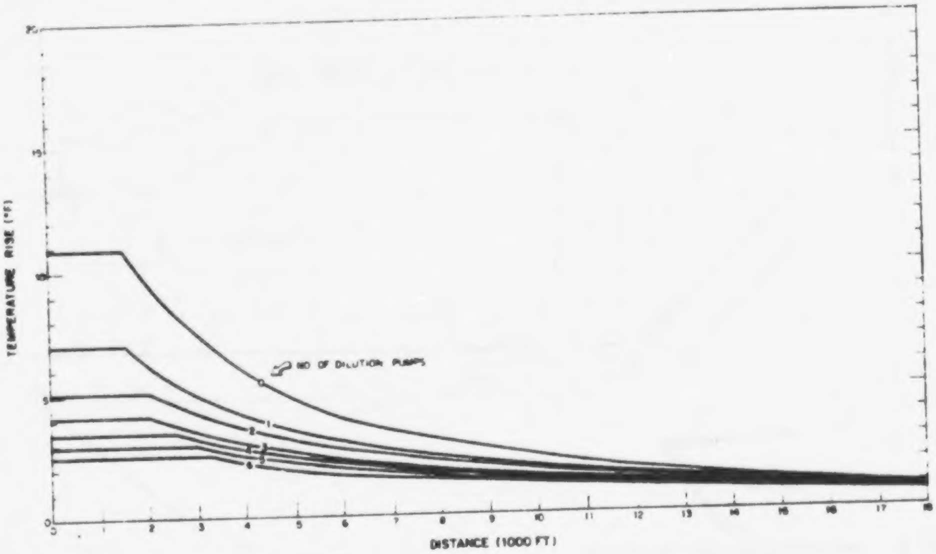


FIGURE 8 TEMPERATURE DECAY CURVES
3 UNITS - 64% LOAD

Big Bend Station
Tampa Electric Company

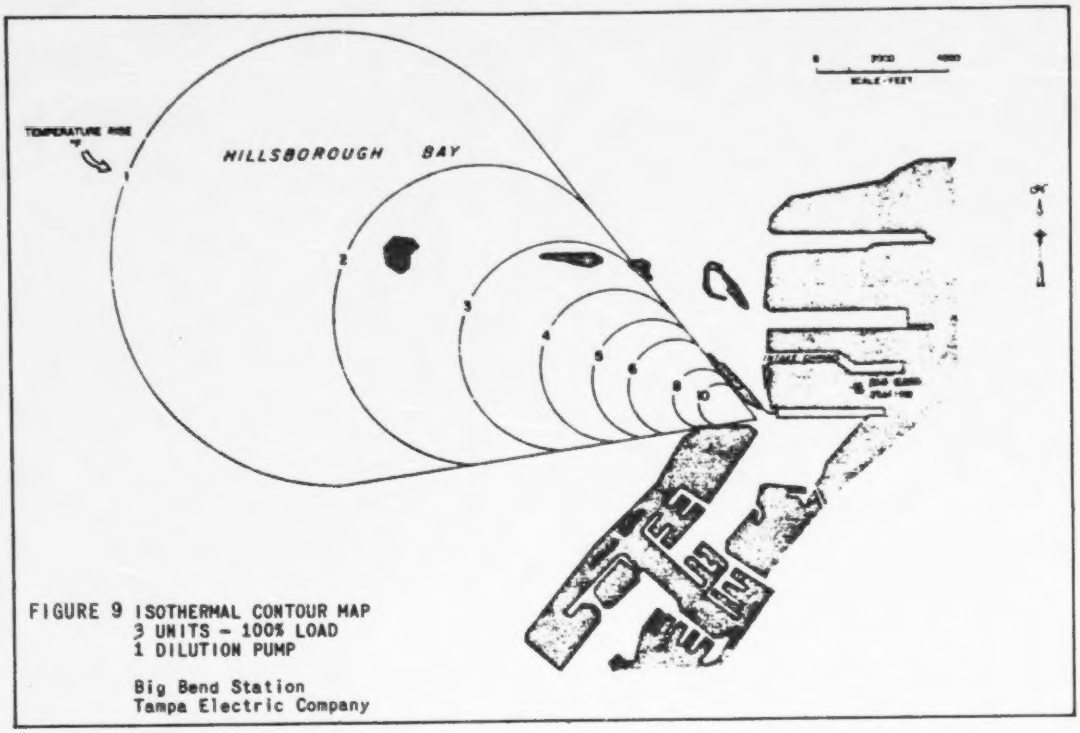

0 2000 4000
SCALE - FEET
TEMPERATURE RISE °F
HILLSBOROUGH BAY
1
2
3
4
5
6
8
10

FIGURE 9 ISOTHERMAL CONTOUR MAP
3 UNITS – 100% LOAD
1 DILUTION PUMP

Big Bend Station
Tampa Electric Company

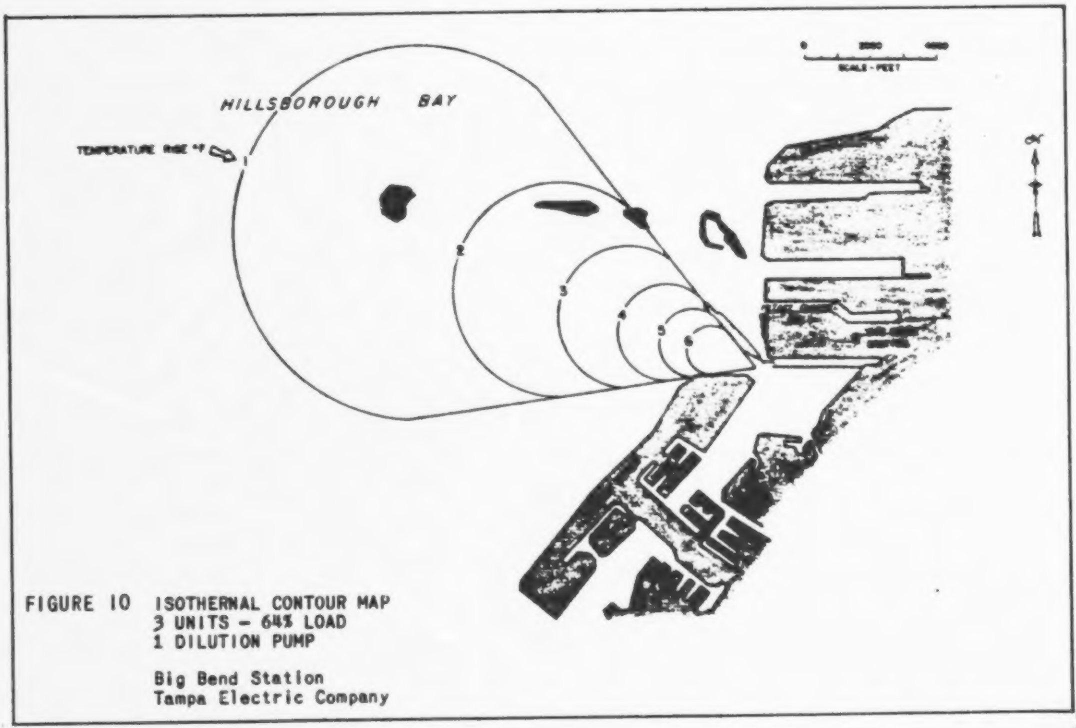

0 2000 4000
SCALE - FEET
HILLSBOROUGH BAY
TEMPERATURE RISE °F
1
2
3
4
5
6

FIGURE 10 ISOTHERMAL CONTOUR MAP
3 UNITS – 64% LOAD
1 DILUTION PUMP

Big Bend Station
Tampa Electric Company

363<

17

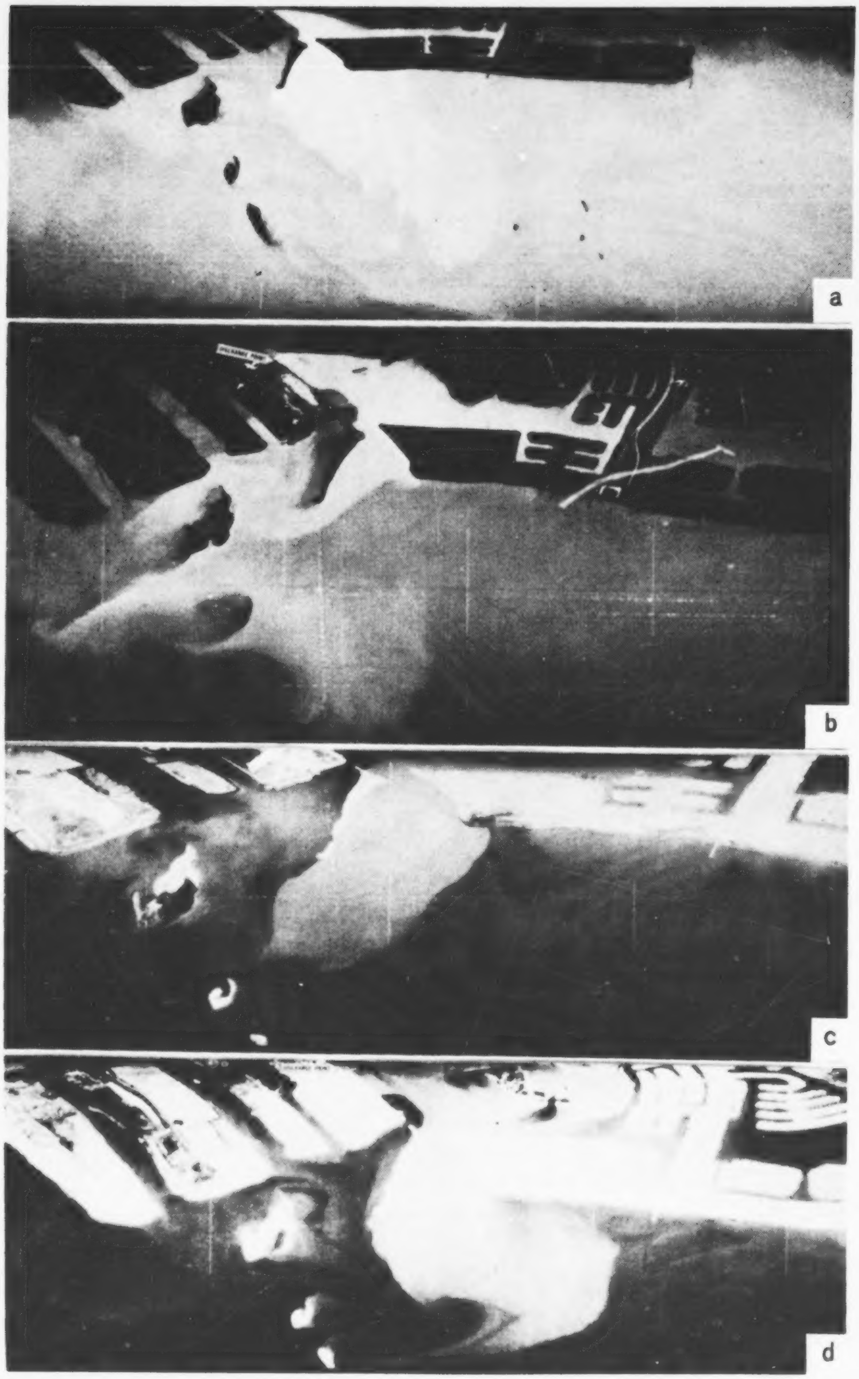


FIGURE 11 AERIAL INFRARED IMAGERY WATER SURFACE TEMPERATURE, SEPTEMBER 16, 1975
Big Bend Station, Tampa Electric Company

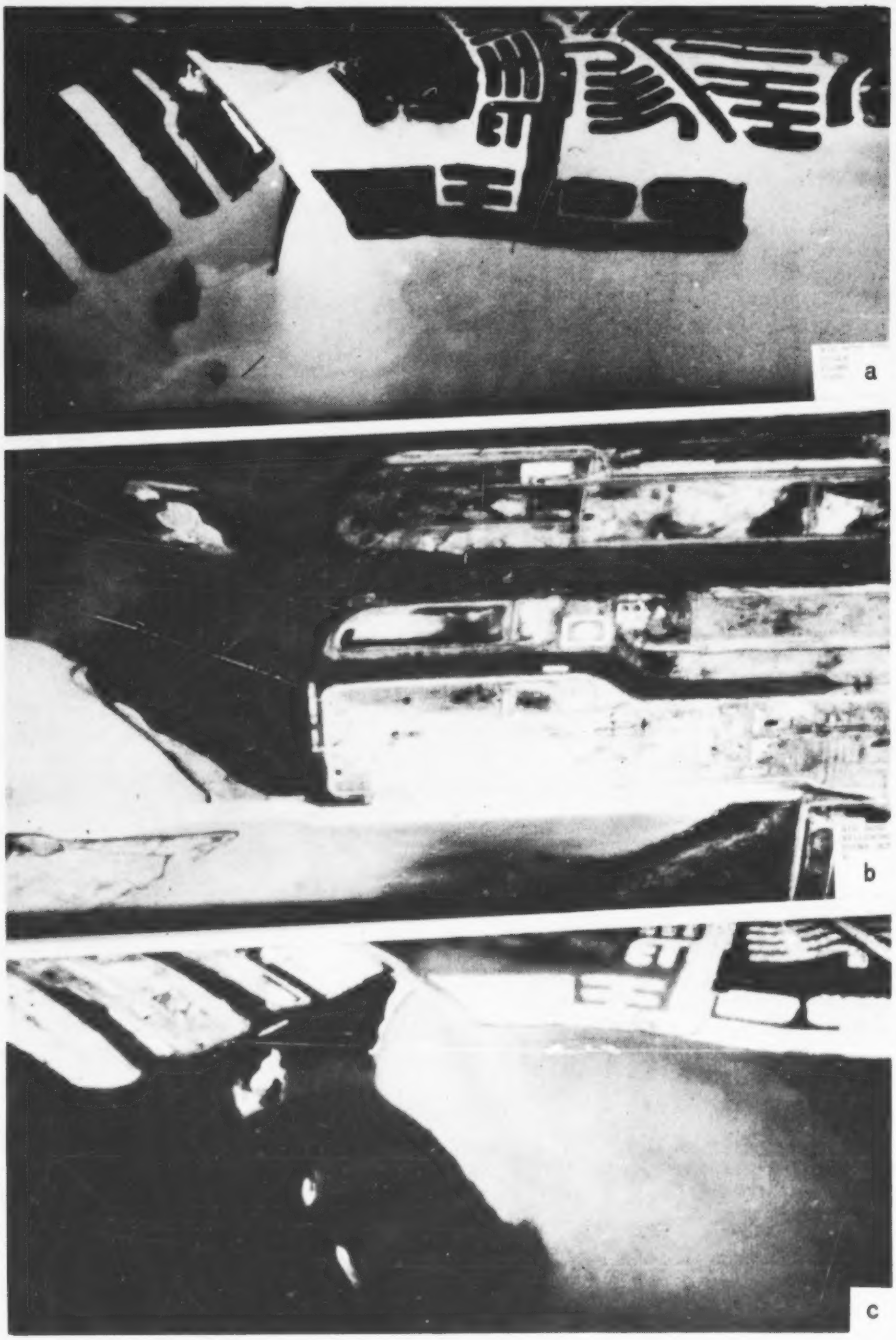


FIGURE 12 AERIAL INFRARED IMAGERY WATER SURFACE TEMPERATURE, OCTOBER 15, 1976

Big Bend Station, Tampa Electric Company

18-45-30

III-C-163

# WET/DRY COOLING FOR WATER CONSERVATION

G. A. Englesson and M. C. Hu
United Engineers and Constructors Inc.
Philadelphia, Pennsylvania U.S.A.

W. F. Savage
U.S. Energy Research and Development Administration
Washington, D.C. U.S.A.

## ABSTRACT

This paper summarizes representative results of a design and cost study of wet/dry tower systems for water conservation. The purpose of the study was to provide design and cost information needed to compare the wet/dry cooling alternative with wet and dry tower systems. The data presented are for 1000 MWe nuclear power plants.

The wet/dry cooling tower concept investigated in this study is one which combines physically separated wet towers and dry towers into an operational system. In designing the cooling system, a dry cooling tower is sized to carry the plant heat load at low ambient temperatures, and a separate wet tower is added to augment the heat rejection of the dry tower at higher ambient temperatures. These cooling systems are designed to operate with a conventional low back pressure turbine commercially available today. The component cooling towers are state-of-the-art designs.

366<

## INTRODUCTION

Consumptive water use is expected to be a major environmental concern in all parts of the United States late in this century [1]. Effective planning for the use of the limited water resources in the United States is in process, especially in the water-deficient areas of the western states [2, 3]. Currently, there is no law which comprehensively and uniformly manages the consumptive use of water in the national interest. As the pressures of industrial, agricultural and municipal growth compete for water use in the future, all consumptive use of water in the United States will be regulated [1].

The competition of all segments of the economy for consumptive use of water is expected to provide a major environmental impact by the end of this century. For this reason, regulators of various state, federal and regional agencies have advocated the use of dry cooling for utility plant applications. In response to requests from these agencies, numerous evaluations have been performed which have indicated: 1) the use of dry cooling would considerably increase the costs of construction and operation of steam electric power plants; 2) their use would result in a significant loss of capacity during the same high temperature conditions when most utilities experience their peak electrical demand; and, 3) the loss of capacity and peak demand are coincident with the time that the environmental impact of consumptive water use is most severe.

This loss of capacity and energy for the dry tower system can significantly be reduced by the use of an evaporative cooling tower to assist the dry tower. Although the addition of a wet helper tower increases the capital cost and consumes water; these towers also reduce the economic penalty associated with the operation of dry cooling by reducing the capacity and energy losses.

Since the water problem in the U.S. was projected to impact on power plant siting and energy growth, the Atomic Energy Commission initiated a design and cost study of wet/dry cooling tower systems designed for water conservation [4]. The program has continued under Energy Research and Development Administration (ERDA) sponsorship. The objective of the study was to provide design and cost information for wet/dry tower systems, and to compare these cooling system alternatives with wet and dry tower systems to determine whether the wet/dry tower concept is an economically viable alternative. Representative results obtained in the study for wet/dry tower systems used in conjunction with 1000 MWe nuclear power plants to reject waste heat while conserving water are presented in this paper.

## SYSTEM DESCRIPTION

The wet/dry cooling tower concept investigated is one which combines physically separated wet towers and dry towers into an operational unit. The

367<
GAE

separate arrangement of wet and dry towers provides flexibility in tower design, operation, and water consumption requirements.

Two arrangements differing in water flow path were selected for the evaluation. One is a series flow arrangement in which the cooling water from the condenser passes first through the dry tower, and then to the wet tower. The other is a parallel flow arrangement in which the cooling water from the condenser divides into two streams and flows through the dry and wet towers in parallel. Figure 1 shows the series flow arrangement while Figure 2 the parallel flow arrangement. Both the component wet and dry towers were assumed to be mechanical draft tower. However, for the series flow arrangement the use of natural draft type instead of mechanical draft type dry tower was also evaluated. Mechanical wet/dry towers with either series or parallel water flow represent the current commercial offering of wet/dry towers for water conservation. The advantage of using natural draft dry towers is that it eliminates the fan power requirement of its mechanical counterpart, even though its capital cost may be greater. These towers are termed: 1) mechanical series wet/dry tower, 2) mechanical parallel wet/dry tower, and 3) natural series wet/dry tower.

In designing the wet/dry tower system, a dry cooling tower is sized to carry the plant heat load at low ambient temperatures. A separate wet tower is added to augment the heat rejection of the dry tower at higher ambient temperatures, such that the turbine back pressure is equal to a specified design value at the highest ambient temperature. These wet/dry towers are designed to operate with conventional low back pressure turbine commercially available today. The component wet and dry towers are state-of-the-art designs.

Two different modes of wet/dry operation were analyzed as shown in Figure 3:

> Mode S1 - The main objective of this mode is to operate the wet helper tower as little as practically possible. During the peak summer ambient temperature, both the wet and dry towers are operating at full capacity. As the ambient temperature falls, the wet cells are turned off in succession to maintain the turbine back pressure essentially constant at the wet tower design value. The back pressure of a typical turbine operating with this system is schematically presented in Figure 3a. When point 3 is reached, all of the wet cells have been shut down and the dry tower can reject the entire heat load. The back pressure curve between points 2 and 3 is saw-tooth shape because a discrete number of wet cells are taken out of service as the ambient temperature and the turbine back pressure decrease. Although operation of the tower system produces a characteristic saw-tooth operation for Mode S1, all subsequent figures will show the wet tower operation at the constant back pressure.

This operational mode requires continuous feedback controls for the operation of the wet towers. Most new stations are being designed with sufficient computer capacity to provide for this additional measure of station control.

Mode S2 - The second mode of operation analyzed represents a system operating with much less control of the wet tower. In this mode, all the wet cells are operated continuously until the dry tower design temperature is reached. As the ambient temperature decreases, the turbine back pressure is allowed to fall. When the dry tower design temperature is reached, all of the wet cells are shut down and the entire heat load is handled by the dry tower. A schematic of this system operation is presented in Figure 3b. As the ambient temperature passes through the dry tower design point, an apparent instantaneous jump in back pressure occurs. Turbine manufacturers have indicated that changes in back pressures of this magnitude occur daily during the operating life of the turbine.

Wet/dry cooling systems operating in the Mode S1 are more water conservative at the expense of greater energy consumption than the same system operating in the Mode S2. Conversely, systems operating in the Mode S2 are more energy conservative at the expense of higher water consumption.

## METHOD OF ANALYSIS

The method used in the economic analysis is a fixed source-fixed demand method as illustrated in Figure 4. A reference plant is assumed to be of fixed heat source, and there is a fixed demand for its output. It is against this fixed demand that the loss of plant performance for each cooling system is measured. Inability to meet this demand will be charged as a penalty cost which is to be added to the capital cost of the cooling system. Other penalty costs include the cost of supplying make-up water and cooling system maintenance cost. The make-up water penalty is of special significance, since availability of water is a primary concern of this study. The sum of the penalty costs and capital cost of a cooling system is called the total evaluated cost (TEC). The nature of these costs is such that an optimum, i.e. minimum total evaluated cost system can be identified as shown in Figure 5.

The fixed heat source of the reference power plant assumed in the analysis is rated at 3173 MW thermal. This heat source may be coupled with either a conventional turbine or a high back pressure turbine. When coupled with the conventional turbine, the generator delivers 1094 MWe at a turbine back pressure of 2 in-HgA (50.8 mm-HgA) as shown in Figure 6. This output, which is assumed to be equal to the fixed demand, is referred to as the base output of the reference plant. The selection of these quantities was based on a typical Light Water Reactor (LWR) plant design as described in Reference [5].

369<

The cooling system evaluation involves sizing and costing a cooling system, determining its thermal performance, water consumption, auxiliary power and energy needs and other requirements during a typical annual cycle. The performance information is used to assess the economic penalties which will accrue over the lifetime of the plant. Finally, from a series of designs which meet certain design criteria and specific water consumption requirement, the minimum cost cooling system is selected. The major components of a cooling system included in the analysis are those shown to the right of Section BB in Figure 7.

## MAJOR RESULTS

The scope of the study includes an extensive evaluation at a base site (Middletown, U.S.A.), and two additional sites. The Middletown site is the ERDA hypothetical site defined as a typical power plant site in the U.S. The pertinent site data used in the analysis are the ambient coincident wet bulb and dry bulb temperatures and the site elevation (sea level). The meteorological conditions for Middletown are modeled after those of Boston, Massachusetts [6].

The major results of the mechanical series wet/dry tower systems for the Middletown site are summarized in this paper as representative of the cooling systems designed for water conservation. The costs obtained are based on the economic factors given in Table 1. The results include a direct comparison of wet/dry cooling with wet and dry cooling.

### Designs and Costs of Wet/Dry Tower Systems

The results for the optimized wet/dry tower systems for various water make-up requirements are shown in Tables 2 through 4. The make-up water requirement is expressed as a percentage of the make-up required by an optimized wet tower system.

Table 2 shows a summary of the major design data for the optimized cooling systems. Included in this table are the tower size and operating mode, the maximum operating back pressure, the gross generator output, the plant heat load at the maximum back pressure, the heat load distribution between the wet and dry towers, and the annual make-up water requirement for the tower system. All of the wet/dry systems had the minimum cost when designed to operate in S1 mode.

Table 2 indicates that wet/dry tower systems of manageable size can be designed for utility applications by shaving the heat load of dry tower with evaporative helper tower. The dry surfaces needed for the wet/dry options are comparable to or less than that required for the dry system using a hypothetical high back pressure turbine. The surface for the dry system using a conventional turbine, however, is over twice the size of that required by the dry system using a high back pressure turbine. The data in Table 2 also show that the capacity deficit (147.3 MWe) incurred on the dry system using the high back pressure turbine can be reduced more than 100 MWe even with the wet/dry system requiring one percent make-up. All wet/dry systems are designed for conventional turbines.

Table 3 summarizes the capital costs and the penalty costs for the tower systems described in Table 2. As previously discussed, the operating penalties are capitalized over the 40 year lifetime of the plant. The total capital cost and the total capacity penalty are both capital dollars which must be expended by the utility owner at the beginning of the plant lifetime. As expected, the sum of the total capital cost and capacity penalty cost is highest for the dry tower system using a low back pressure turbine and the lowest for the wet system using the same turbine.

For the wet/dry systems, the costs range between the dry and the wet systems; the costs of the wet/dry systems decrease monotonically as the make-up water requirement is allowed to increase (see Figure 8). The total evaluated costs for all of the wet/dry systems are significantly lower than that for the dry systems, but significantly higher than the wet systems. As shown in Figure 8 and in Table 3, the total evaluated cost for the one percent wet/dry system is over 21 percent lower than the cost of the two dry systems; the total evaluated cost for the 40 percent wet/dry system is 70 percent higher than the cost of the wet system.

The major capital and penalty cost elements are itemized in Table 4. The data indicate that the tower cost of each of the wet/dry systems constitutes approximately 50 percent of the capital cost of the cooling system and approximately 30 percent of the total evaluated cost.

## Plant Performance

An example of the plant performance for a wet/dry system is shown in Figure 9 for a 10 percent make-up wet/dry tower system operating in the S1 mode. The performance shown includes the gross and net generator output, turbine back pressure, and make-up flow rate over an annual cycle.

When the wet and dry towers are operating together, the turbine back pressure is maintained near its design value of 4.5 in-HgA (114.3 mm-HgA), and the gross plant output (MWe) is at its lowest value. The wet tower modules are gradually taken out of service as the ambient temperature decreases. The dry tower takes over completely when it is able to carry the plant heat load while maintaining the turbine back pressure below the design value. At this point, all the wet towers are out of service and no water is required as shown by the make-up curve. When the dry tower operates alone, in response to the falling dry bulb temperature, the efficiency of the dry tower system increases, resulting in lower back pressure and greater gross and net generator outputs. The gross plant output reflects the back pressure variation as described above.

A comparison of the gross generator output for different percentage make-up wet/dry and reference systems is shown in Figure 10. The corresponding ambient temperatures at which the cooling system and plant performance were determined are shown superimposed on the figure.

The constant gross generator output for the wet/dry systems reflects back pressure differences of 0.5 in (12.7 mm) of HgA and approximately 11 MWe difference in generator output. Although the lower fraction make-up systems suffer larger capacity reductions, operations of their larger dry systems result in shorter durations of combined wet and dry tower operation where the maximum capacity deficit occurs.

Integration of the capacity deficit over the annual cycle determines the amount of replacement energy required for the wet/dry and the reference systems. The amount of replacement energy is represented in Figure 10 by the area bound between the constant base output line and the gross output curve for each cooling system. The figure clearly shows the relative magnitude of the replacement energy needed by the wet/dry, wet and dry systems. It also shows that the higher percentage make-up wet/dry systems require more replacement energies than the lower percentage make-up systems. This is obvious between the 1 and 10 percent systems and also between the 30 and 40 percent systems. This situation occurs because the lower percentage make-up systems require a large number of dry cells to control water consumption. Operation of these large number of dry cells at low ambient temperatures allow these systems to attain lower back pressure than the controlled constant operating back pressure. Consequently, the plant operates at higher gross output during a part of the year, resulting in lower replacement energy requirement. The amounts of replacement energy required by different cooling systems are also reflected in the replacement energy penalty costs tabulated in Table 4.

A comparison of the net generator output for those systems represented in Figure 10 is shown in Figure 11. Examination of these curves shows that the total energy which must be replaced with reference to the fixed demand is essentially constant over the annual cycle and independent of the water consumption for all of the wet/dry systems designed. This information can be verified in Table 4 where the sum of the replacement energy and the auxiliary energy cost are approximately constant. It follows that the net available energy (MW-hrs), independent of the make-up requirement, is approximately constant for all of the mechanical series wet/dry systems operating in S1 mode. Thus, the cost for conserving water for the wet/dry systems is derived directly from the sum of the capital cost of the cooling system and the capital cost of the make-up capacity including the auxiliary power requirement.

## Water Usage

One of the criteria used in the design of an optimum wet/dry tower is the annual make-up requirement. The annual make-up is determined as the summation of the water usage during each interval of an ambient temperature cycle. Since most streams generally have a low stream flow in summer when the cooling tower make-up requirements are the highest, it is important to determine the water usage requirements on a monthly or a daily basis during the annual cycle.

Figure 12 shows the total amount of make-up required for each month during a typical annual cycle. Figure 13 shows the maximum make-up flow rate during each month. Although the annual percentage make-up is small, the maximum flow rate can be large. For example, even for the one percent make-up system, the maximum make-up flow rate is almost one third of that required by the wet system because the system requires about a third of the wet cells needed for the wet tower. Total monthly requirement, however, is less than ten percent of the wet system requirement. The information given in Figures 12 and 13 can be used to determine whether stream flow conditions match the make-up requirements, or to size the reservoir or impoundment necessary for station operation.

## Water Costs

In this study, wet/dry tower systems were optimized for specific make-up water requirements. This method of approach was designed to allow the optimization to be independent of water supply cost. Since all of the systems designed for a specific make-up requirement require the same amount of water and have the same make-up supply penalty cost, any change in water supply cost will not affect the optimization of a wet/dry system requiring the specified make-up. The advantage of this method is that site specific water supply costs in excess of the base water costs can be determined for each make-up requirement, and can then be added directly to the total evaluated costs for the wet and wet/dry cooling systems for the purpose of economic comparison.

There are many factors which influence the water supply cost for specific sites; among them distance, terrain, elevation changes and legal requirements. The water supply costs should be developed during a preliminary engineering or site selection phase of an engineering program and added to total evaluated cost to compare the systems.

The impact of water supply cost on the economic comparison is demonstrated in Figure 14. Two different types of water cost analysis were prepared for Middletown. To address the general impact of water supply cost, uniform water costs were incrementally added to the base cost. The basic analysis was performed for water costs of \$0.27/1000 gal (\$0.07/$m^3$). This base cost was estimated on the basis of current utility practice for a plant sited adjacent to a river with fresh water make-up. For a general site where water must be purchased and extensively treated to prevent scaling or corrosion in cooling towers, this base cost can be regarded as representing the water purchase and treatment costs. The cost was increased to \$2/1000 gal (\$0.53/$m^3$) and then in \$2 (\$0.53) increments to \$8/1000 gal (\$2.12/$m^3$).

For study purposes, the general water cost results provide an indication of the approximate break-even water cost for wet/dry versus wet cooling (shown in Figure 14) as approximately \$4.50/1000 gal (\$1.19/$m^3$). This cost amounts to a water supply requirement \$100 million in excess of the total evaluated cost for the optimized evaporative cooling system using the base water cost.

For comparison with this general type analysis, a specific analysis for a hypothetical condition at the Middletown site was also prepared. The river which provides the make-up supply is assumed to be 29 miles (46.7 km) from the plant. In addition, the river has legal restrictions on water consumption which requires a major impoundment for the wet tower. The results of this analysis are shown superimposed on Figure 14. This figure shows that the lowest cost wet/dry system is the 40 percent make-up system, and it is 36 million dollars more expensive than the wet system. This cost difference is considerably smaller than the 69 million dollar difference obtained with the base water cost, but the wet system remains the economic choice over the wet/dry system.

These data indicate that a high water supply cost is required to make wet/dry cooling economically comparable to that of wet cooling. Water availability coupled with legal requirements or other environmental constraints will dictate whether wet/dry cooling should be used for nuclear power plants.

## CONCLUSIONS

1. Wet/dry cooling systems can be designed to provide a significant economic advantage over dry cooling yet closely matching the dry tower's ability to conserve water. A wet/dry system which saves as much as 99 percent of the make-up required by a wet tower can maintain that economic advantage. Therefore, for power plant sites where water is in short supply, wet/dry cooling is the economic choice over dry cooling.

2. Where water is available, wet cooling will continue to be the economic choice in most circumstances. Only if resource limitation or environmental criteria make water costs excessive, can wet/dry cooling become economically in par with wet cooling.

3. The economic advantage of wet/dry cooling over dry cooling reduces the need for further development of high back pressure turbines for nuclear power plant applications.

4. The dry surfaces needed for wet/dry options are, in general, less than that required for the dry cooling systems using the high back pressure turbines, but remain large in size. Therefore, the development of improved dry surfaces should be continued for use in wet/dry cooling.

## ACKNOWLEDGEMENTS

The work reported in [4] was supported by the U.S. Energy Research and Development Administration under Contract No. E(11-1)-2442. The project was completed under the direction of W. F. Savage, Project Officer of ERDA and J. H. Crowley, Manager of the Advanced Engineering Department, United Engineers and Constructors Inc. In addition to the authors, the following individuals at UE&C contributed to the completion of the work: J. C. Bentz, S. R. Buerkel, N. H. Lee, D. E. Pennline, and C. M. Valorie.

REFERENCES

1. A. M. Piper, Has the United States Enough Water?, Geological Survey Water Supply Paper 1797, United States Government Printing Office, Washington, D.C., 1965.

2. E. F. Gloyna, H. H. Woodson and H. R. Drew, Editors, Water Management By The Electric Power Industry, Water Resources Symposium Number Eight, Center for Research in Water Resources, The University of Texas at Austin, 1975.

3. Western States Water Requirements for Energy Development to 1990, Western States Water Council, Salt Lake City, Utah, November 1974.

4. Engineering and Economic Evaluation of Wet/Dry Cooling Towers for Water Conservation, UE&C-ERDA-761130, United Engineers and Constructors Inc., Philadelphia, Pa., November 1976.

5. 1000 MWe Central Station Power Plants - Investment Cost Study, Volumes I and II, WASH-1230, United Engineers and Constructors Inc., Philadelphia, Pa., 1972.

6. Engineering Weather Data, AFM 88-8, Chapter 6, TM 5-785, and NAVFAC P-89, Departments of the Air Force, the Army, and the Navy, June 1967.

375<

GAE

TABLE 1a

## BASIC ECONOMIC FACTORS

| | |
|---|---|
| PLANT START-UP DATE | 1985 |
| AVERAGE PLANT CAPACITY FACTOR | 0.75 |
| ANNUAL FIXED CHARGE RATE | 18% |
| PLANT LIFE | 40 YEARS |
| CAPACITY PENALTY CHARGE RATE (INCREMENTAL BASE LOAD PLANT COST) | \$600/KW |
| FUEL COST (FOR BASE LOAD PLANT) | 153c/MBTU (145c/GJ) |
| OPERATION AND MAINTENANCE COST (FOR INCREMENTAL BASE LOAD PLANT) | 0.724 MILLS/KWHR |
| WATER COST | 27c/1000 GAL (7.13c/$M^3$) |

TABLE 1b

## FACTORS FOR ESCALATION

| | |
|---|---|
| CONSTRUCTION PERIOD FOR LWR | 6 YEARS |
| CONSTRUCTION PERIOD FOR COOLING SYSTEM | 2 YEARS |
| ESCALATION ON OVERALL PLANT COSTS | 7% PER YEAR |
| ESCALATION ON COOLING SYSTEM EQUIPMENT AND MATERIAL | 6% PER YEAR |
| ESCALATION ON COOLING SYSTEM LABOR | 8% PER YEAR |
| ESCALATION FOR FUEL COST LEVELIZATION | 4% PER YEAR |
| INTEREST RATE | 10% PER YEAR |
| BASE YEAR COST DATA | 1974 |

377<

TABLE 2

## MAJOR DESIGN DATA FOR THE OPTIMIZED COOLING TOWER SYSTEMS

SITE: MIDDLETOWN U. S. A. BASE OUTPUT: 1094 MWE WET/DRY TYPE: MECHANICAL SERIES (S1)

| ITEM | MECH. DRY (H)* | MECH. DRY (L)† | PERCENTAGE MAKE–UP REQUIREMENT MECHANICAL SERIES WET/DRY | | | | | MECH. WET |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| NUMBER OF TOWER CELLS, WET TOWER/DRY TOWER | 0/156 | 0/338 | 13/192 | 19/136 | 26/114 | 27/90 | 30/79 | 33/0 |
| MODE OF WET/DRY TOWER OPERATION | – | – | S1 | S1 | S1 | S1 | S1 | – |
| MAXIMUM OPERATING BACK PRESSURE $P_{MAX}$, IN–HGA (MM–HGA) | 12.51<br>(317.8) | 5.06<br>(128.5) | 5.0<br>(127.0) | 4.5<br>(114.3) | 4.0<br>(101.6) | 4.0<br>(101.6) | 4.0<br>(101.6) | 3.90<br>(99.1) |
| GROSS PLANT OUTPUT AT $P_{MAX}$, MWE | 946.7 | 1046.8 | 1048.4 | 1059.5 | 1069.9 | 1069.9 | 1069.9 | 1071.9 |
| HEAT LOAD AT $P_{MAX}$, $10^9$ BTU/HR ($10^{12}$ J/HR) | 7.60<br>(8.02) | 7.26<br>(7.66) | 7.25<br>(7.65) | 7.22<br>(7.61) | 7.18<br>(7.57) | 7.18<br>(7.57) | 7.18<br>(7.57) | 7.17<br>(7.57) |
| HEAT LOAD DISTRIBUTION AT $P_{MAX}$, (WET TOWER/ DRY TOWER), % | 0.0/<br>100.0 | 0.0/<br>100.0 | 42.7/<br>57.3 | 63.7/<br>36.3 | 73.8/<br>26.2 | 78.2/<br>21.8 | 80.5/<br>19.5 | 100.0/<br>0.0 |
| ANNUAL MAKE–UP WATER FOR WET TOWERS, $10^8$ GAL ($10^6$ $M^3$) | 0.0<br>(0.0) | 0.0<br>(0.0) | 0.435<br>(0.165) | 4.40<br>(1.66) | 8.45<br>(3.20) | 13.29<br>(5.03) | 16.35<br>(6.19) | 42.34<br>(16.06) |

* H–HIGH BACK PRESSURE TURBINE
† L–CONVENTIONAL LOW BACK PRESSURE TURBINE

378<

TABLE 3

**MAJOR COST SUMMARY FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)**

SITE: MIDDLETOWN, U.S.A.

WET/DRY TYPE: MECHANICAL SERIES (S1)

| ITEM | MECH. DRY (H)* | MECH. DRY (L)† | PERCENTAGE MAKE-UP REQUIREMENT MECHANICAL SERIES WET/DRY | | | | | MECH. WET |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| TOTAL CAPITAL COST (DIRECT & INDIRECT CAPITAL COSTS) | 108.82 | 215.54 | 146.83 | 118.96 | 111.82 | 100.76 | 96.44 | 54.44 |
| TOTAL CAPACITY PENALTY (CAPACITY & AUXILIARY POWER) | 108.32 | 66.35 | 51.85 | 40.95 | 33.90 | 32.95 | 32.17 | 22.65 |
| TOTAL OPERATING PENALTY (REPLACEMENT & AUXILIARY ENERGIES, MAKE-UP WATER & MAINTENANCE) | 80.16 | 43.89 | 35.15 | 35.99 | 35.45 | 37.99 | 38.23 | 21.01 |
| TOTAL EVALUATED COST (SUM OF CAPITAL & PENALTY COSTS) | 297.30 | 325.78 | 233.83 | 195.90 | 181.17 | 171.70 | 166.84 | 98.10 |

* H–HIGH BACK PRESSURE TURBINE
† L–CONVENTIONAL LOW BACK PRESSURE TURBINE

## TABLE 4

## MAJOR CAPITAL AND PENALTY COST COMPONENTS FOR OPTIMIZED COOLING TOWER SYSTEMS ($\$10^6$)

SITE: MIDDLETOWN, U.S.A.

WET/DRY TYPE: MECHANICAL SERIES (S1)

| ITEM | MECH. DRY(H)* | MECH. DRY (L)† | PERCENTAGE MAKE-UP REQUIREMENT MECHANICAL SERIES WET/DRY | | | | | MECH. WET |
|---|---|---|---|---|---|---|---|---|
| | | | 1% | 10% | 20% | 30% | 40% | |
| CAPITAL COST: | | | | | | | | |
| COOLING TOWER | 54.42 | 116.90 | 74.56 | 58.59 | 55.07 | 47.27 | 45.22 | 19.48 |
| CONDENSER | 15.20 | 20.88 | 15.98 | 14.11 | 13.64 | 13.62 | 13.25 | 13.61 |
| CIRCULATING WATER SYSTEM | 10.02 | 17.92 | 14.74 | 13.01 | 12.23 | 12.35 | 11.77 | 8.22 |
| ELECTRICAL EQUIPMENT | 7.32 | 15.72 | 12.18 | 9.46 | 8.52 | 7.37 | 6.91 | 2.25 |
| INDIRECT COST | 21.86 | 44.12 | 29.37 | 23.79 | 22.36 | 20.15 | 19.29 | 10.88 |
| TOTAL CAPITAL COST | 108.82 | 215.54 | 146.83 | 118.96 | 111.82 | 100.76 | 96.44 | 54.44 |
| PENALTY COST: | | | | | | | | |
| CAPACITY | 88.97 | 28.33 | 27.36 | 20.72 | 14.46 | 14.46 | 14.44 | 13.27 |
| AUXILIARY POWER | 19.35 | 38.02 | 24.49 | 20.23 | 19.44 | 18.49 | 17.73 | 9.38 |
| REPLACEMENT ENERGY | 55.56 | 0.29 | 5.48 | 11.39 | 11.34 | 13.74 | 14.25 | 3.07 |
| AUXILIARY ENERGY | 19.23 | 33.03 | 22.33 | 17.71 | 17.02 | 16.89 | 16.34 | 9.02 |
| MAKE-UP WATER | 0 | 0 | 0.06 | 0.65 | 1.25 | 1.97 | 2.42 | 6.28 |
| COOLING SYSTEM MAINTENANCE | 5.37 | 10.57 | 7.28 | 6.24 | 5.84 | 5.39 | 5.22 | 2.64 |
| TOTAL PENALTY | 188.48 | 110.24 | 87.01 | 76.94 | 69.35 | 70.94 | 70.40 | 43.66 |

*H–HIGH BACK PRESSURE TURBINE
†L–CONVENTIONAL LOW BACK PRESSURE TURBINE

380<

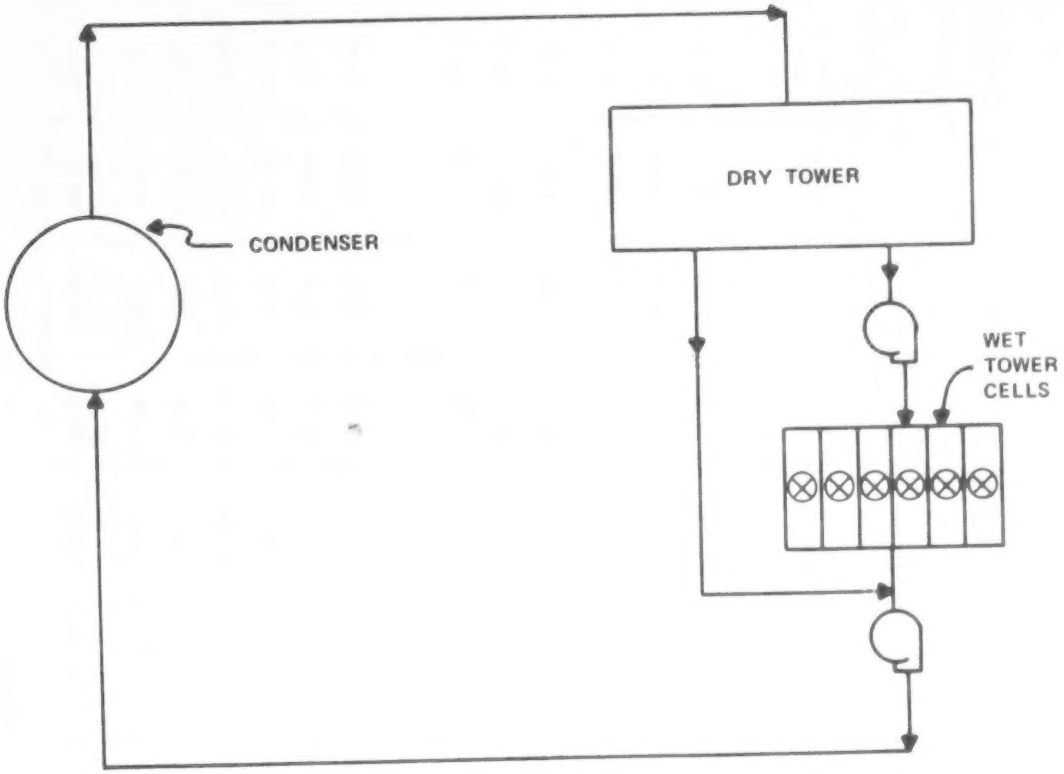

DRY TOWER
CONDENSER
WET TOWER CELLS

Figure 1 Series-Water Flow Wet/Dry Tower

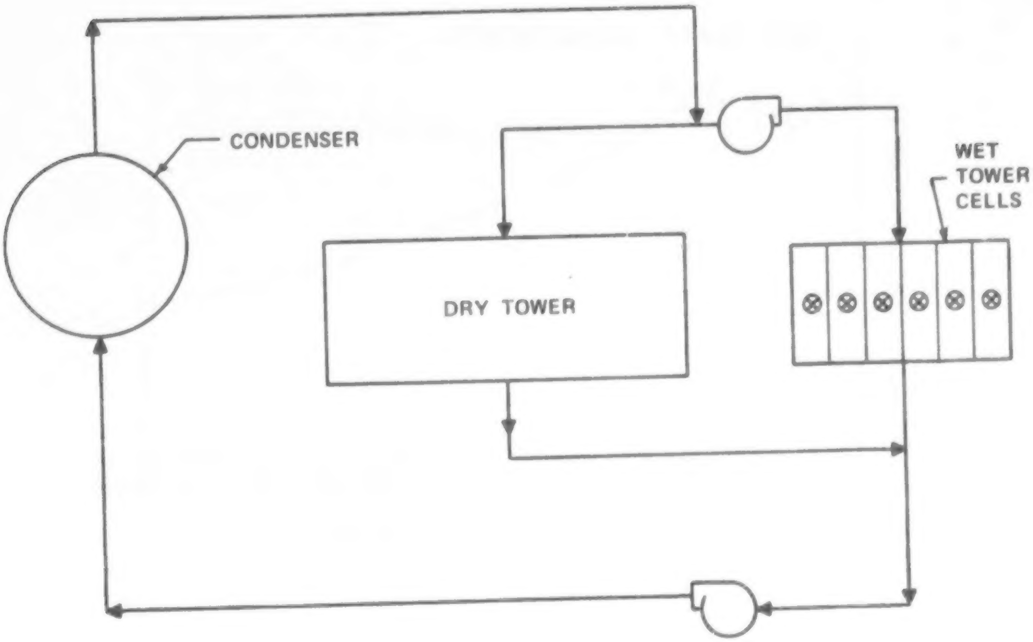

CONDENSER
WET
TOWER
CELLS
DRY TOWER

Figure 2 Parallel-Water Flow Wet/Dry Tower

382<

GAE

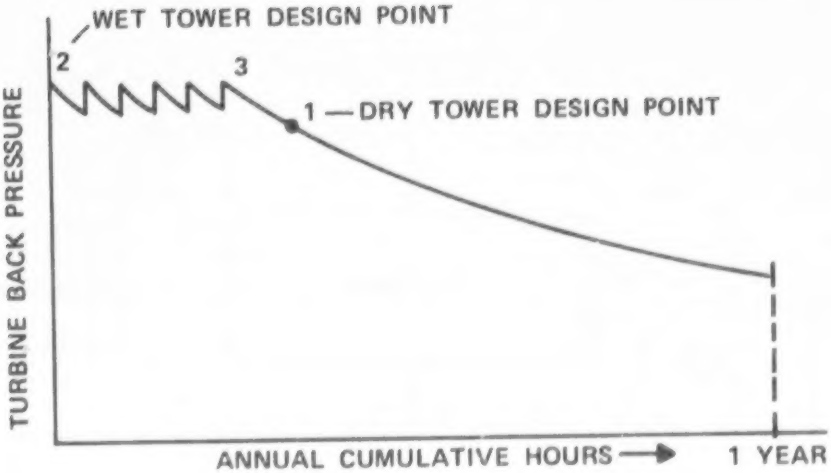


Figure 3a Wet/Dry Tower-Mode S1 Operation

383<

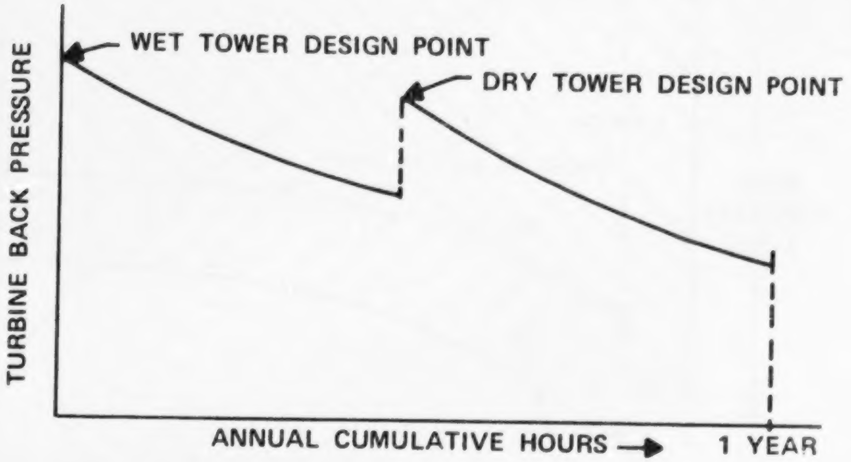


Figure 3b Wet/Dry Tower-Mode S2 Operation

384<

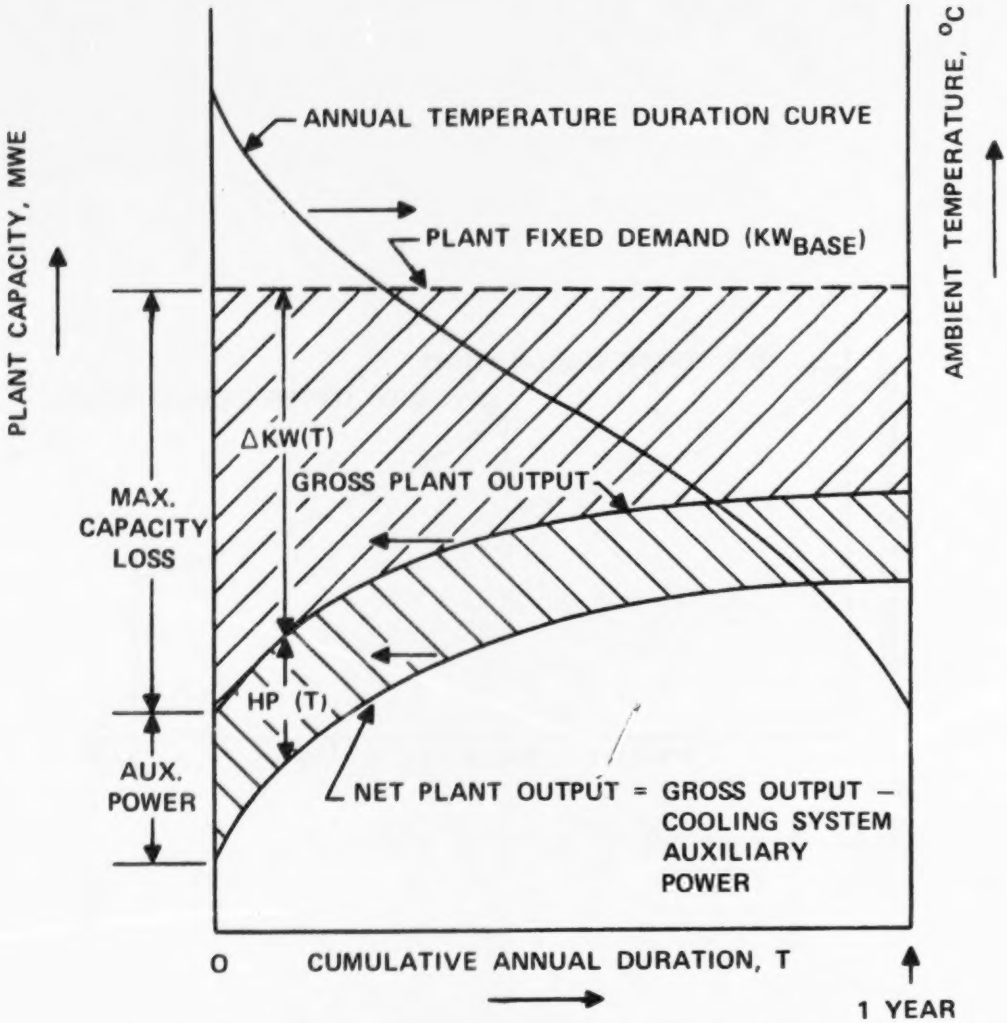


Figure 4 Ambient Temperature Duration And Corresponding Plant Performance

385<

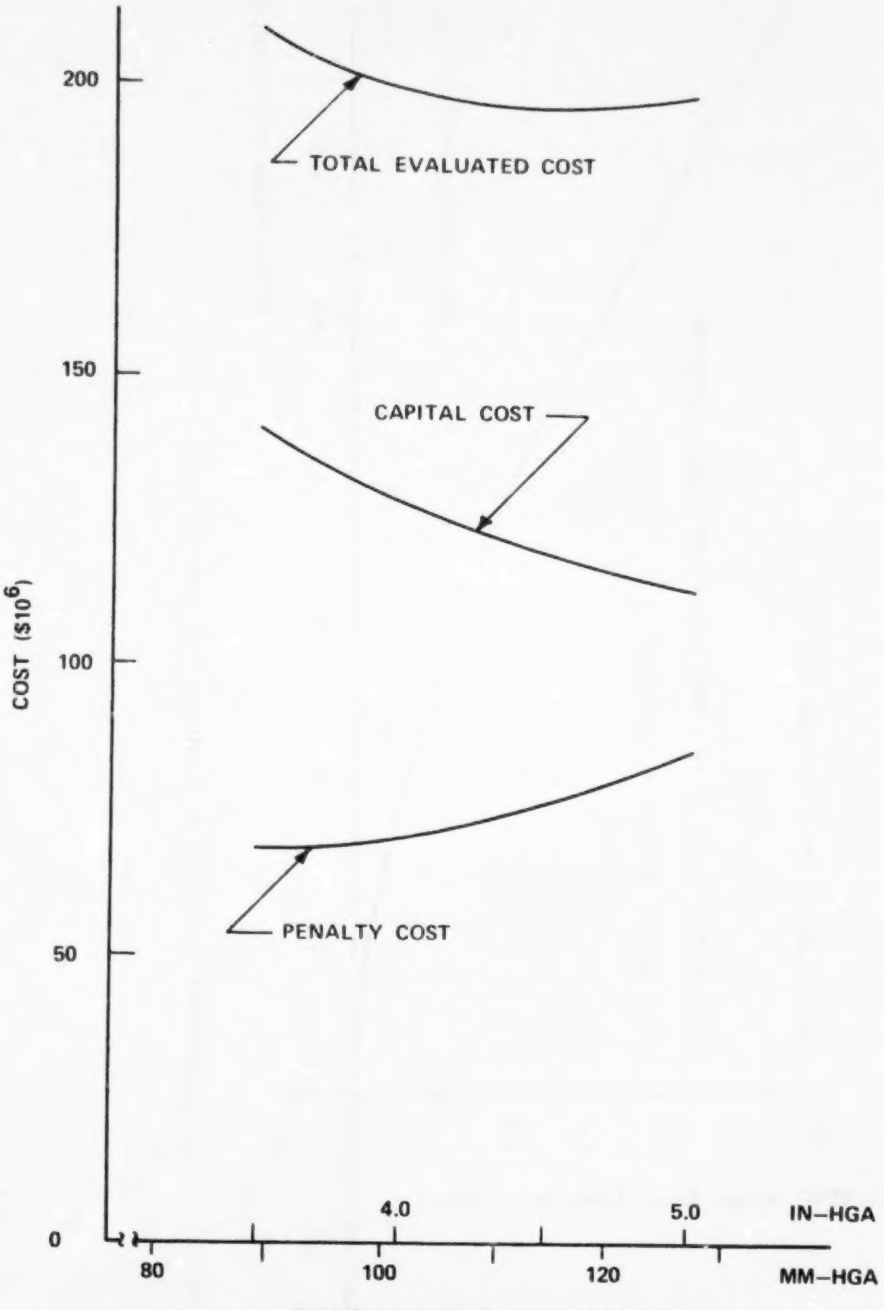


Figure 5 Optimum Selection And Economic Trade-offs
Of A 10 Percent Wet/Dry System
(Middletown, Mechanical Series, S1 Mode)

386<

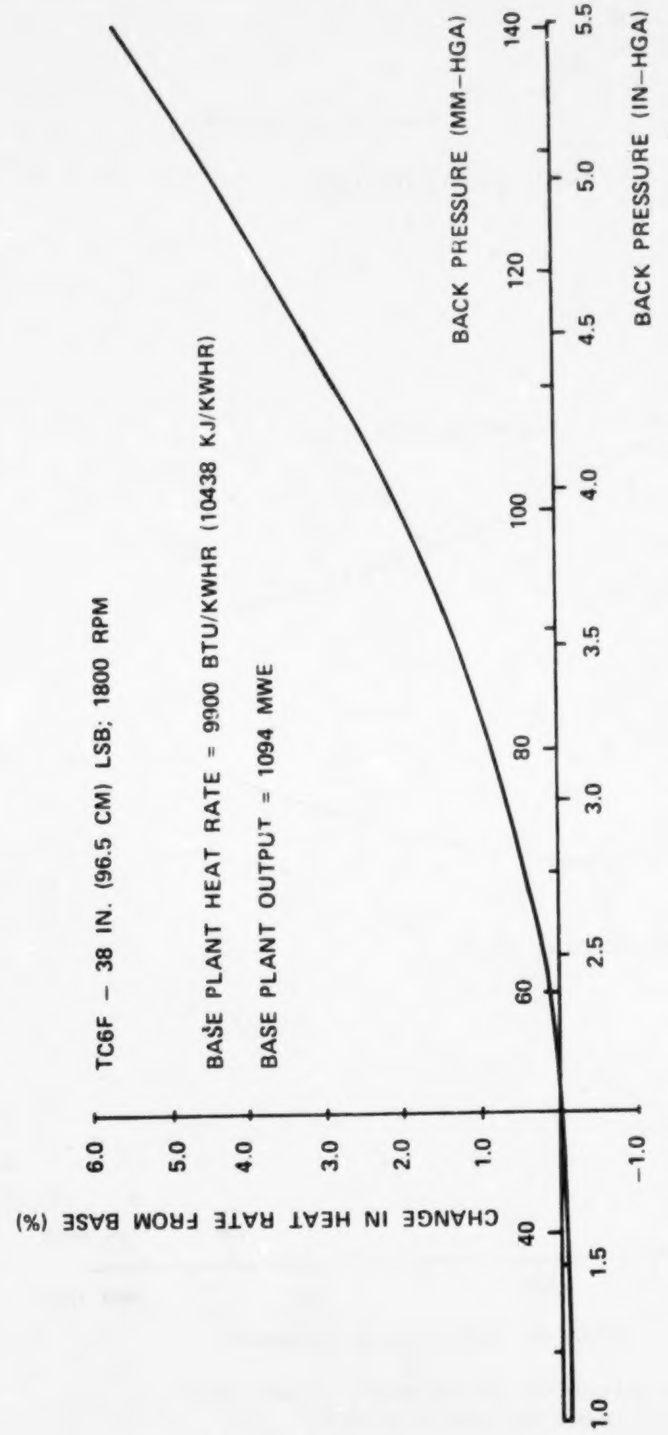


Figure 6 Heat Rate Correction Curve For A Plant With A Conventional Turbine

387<

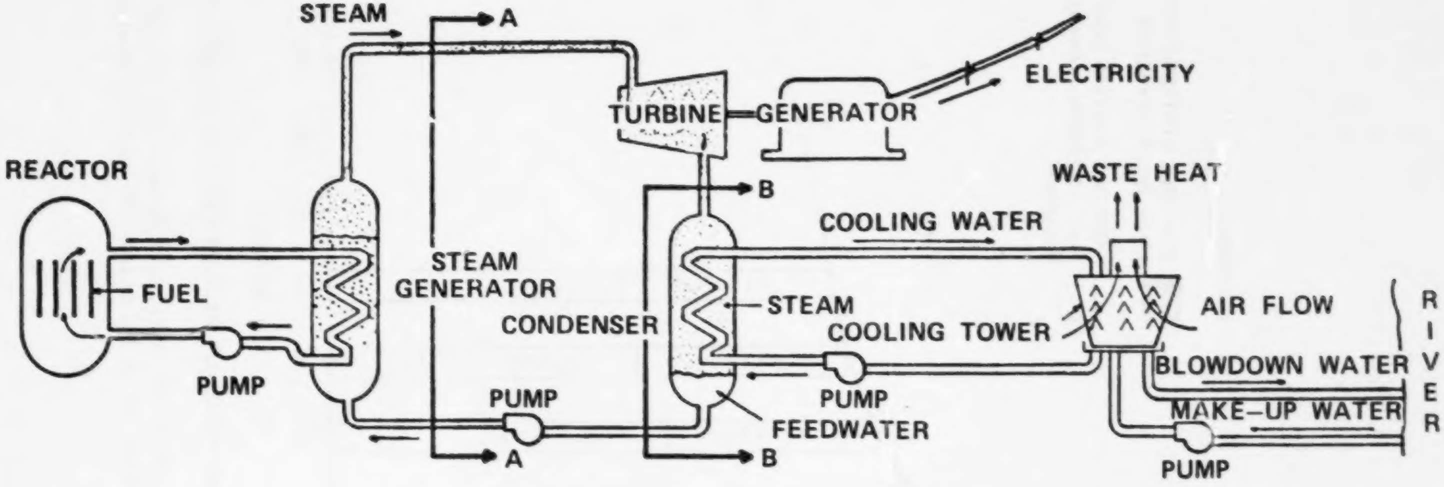

STEAM
A
REACTOR
FUEL
PUMP
STEAM GENERATOR
TURBINE
GENERATOR
ELECTRICITY
CONDENSER
PUMP
A
B
B
STEAM
COOLING WATER
WASTE HEAT
COOLING TOWER
AIR FLOW
PUMP
FEEDWATER
BLOWDOWN WATER
MAKE-UP WATER
PUMP
RIVER

Figure 7 Power Generation and Waste Heat Rejection - Pressurized Water Reactor (PWR) With Evaporative Cooling Tower

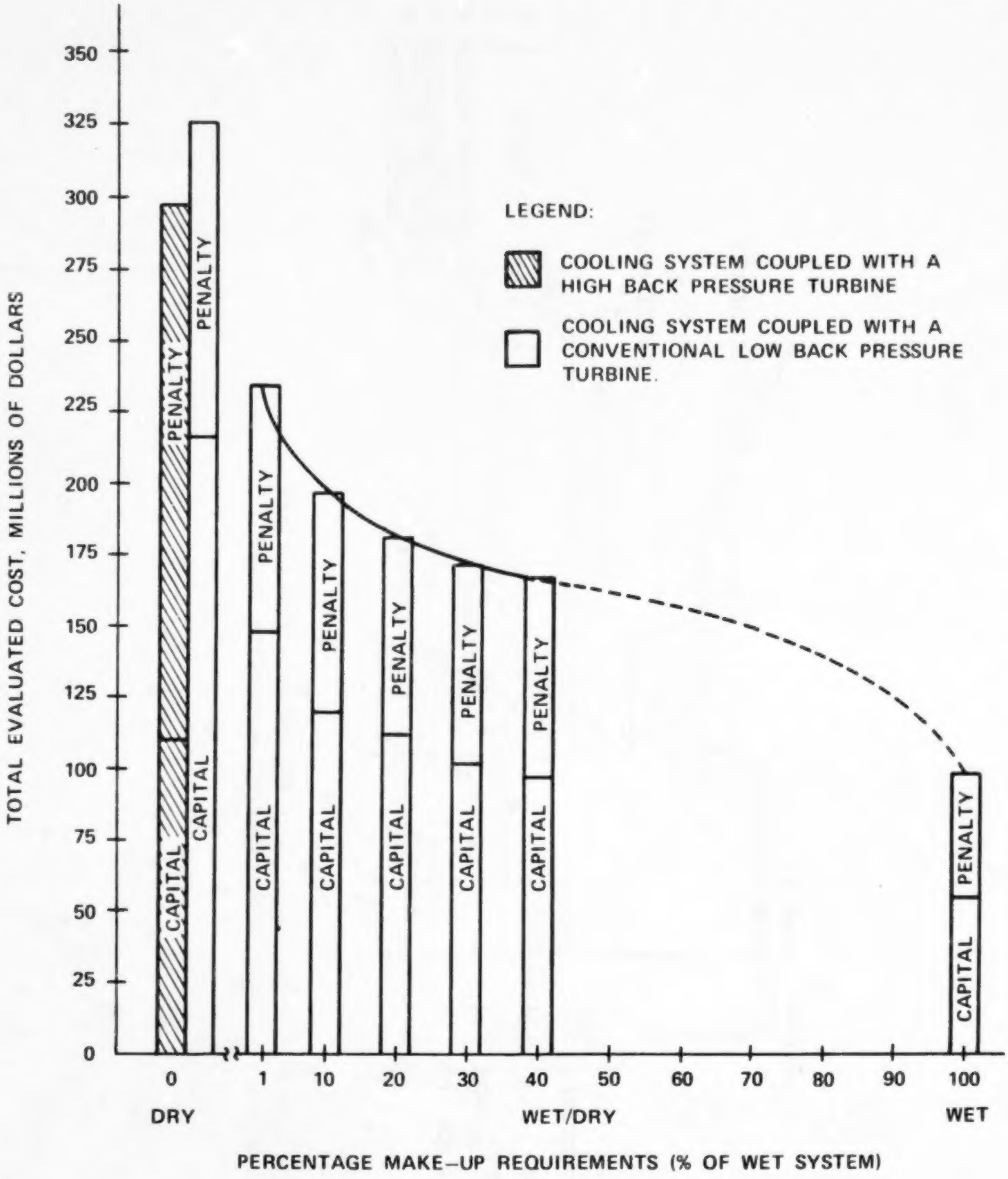


Figure 8 Total Evaluated Cost of Cooling Systems For A 1000 MWe Nuclear Power Plant As A Function Of Varying Amounts Of Water Used

389<

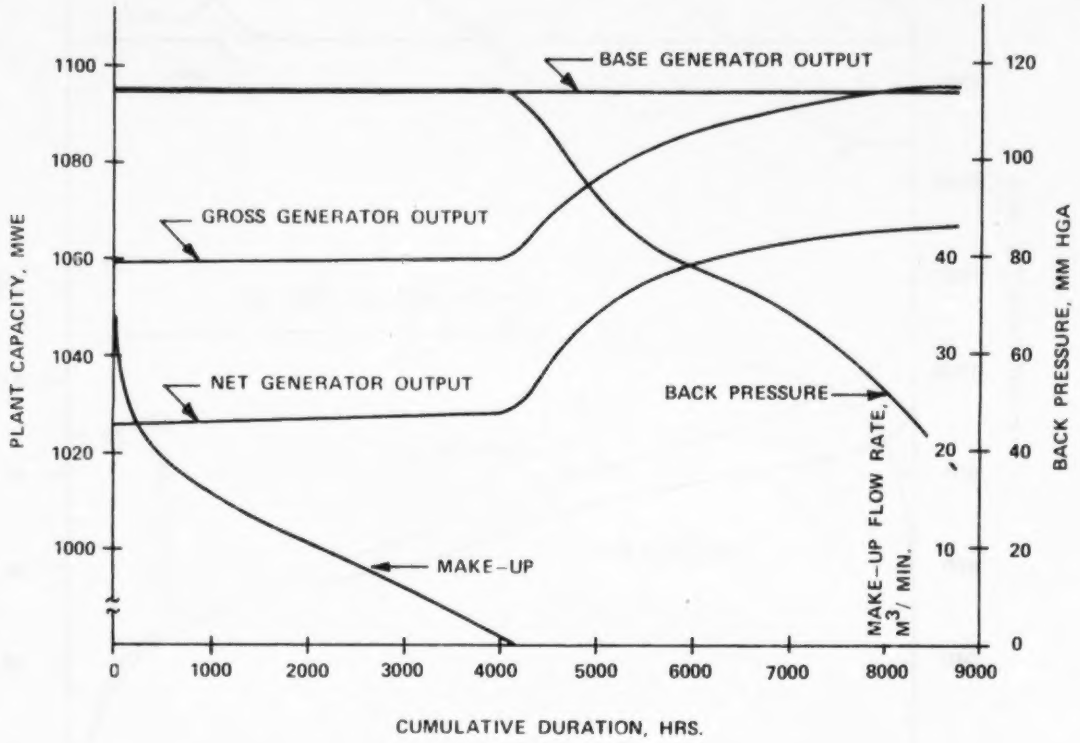


Figure 9 Performance Curves For A 10% Wet/Dry Cooling System Middletown

390<

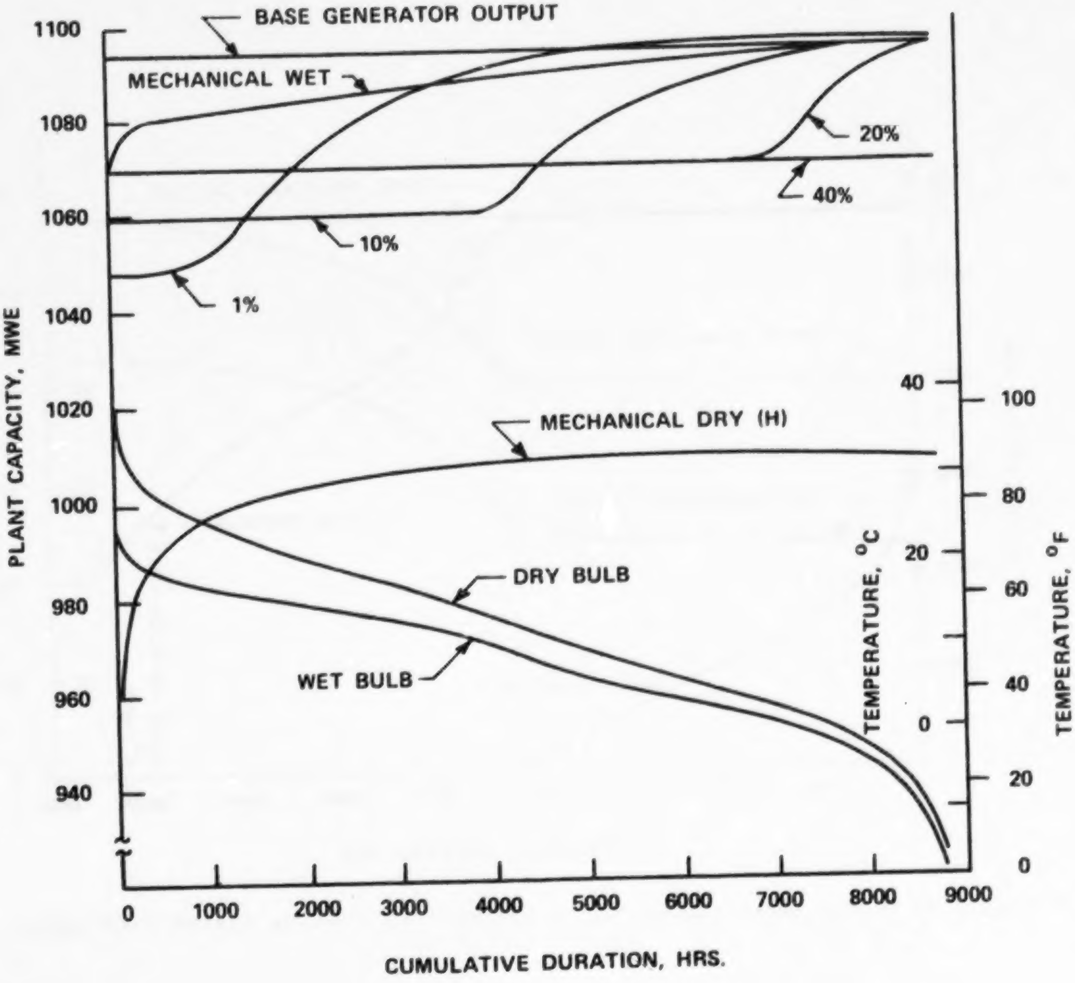


Figure 10 Gross Generator Output - Middletown

391<

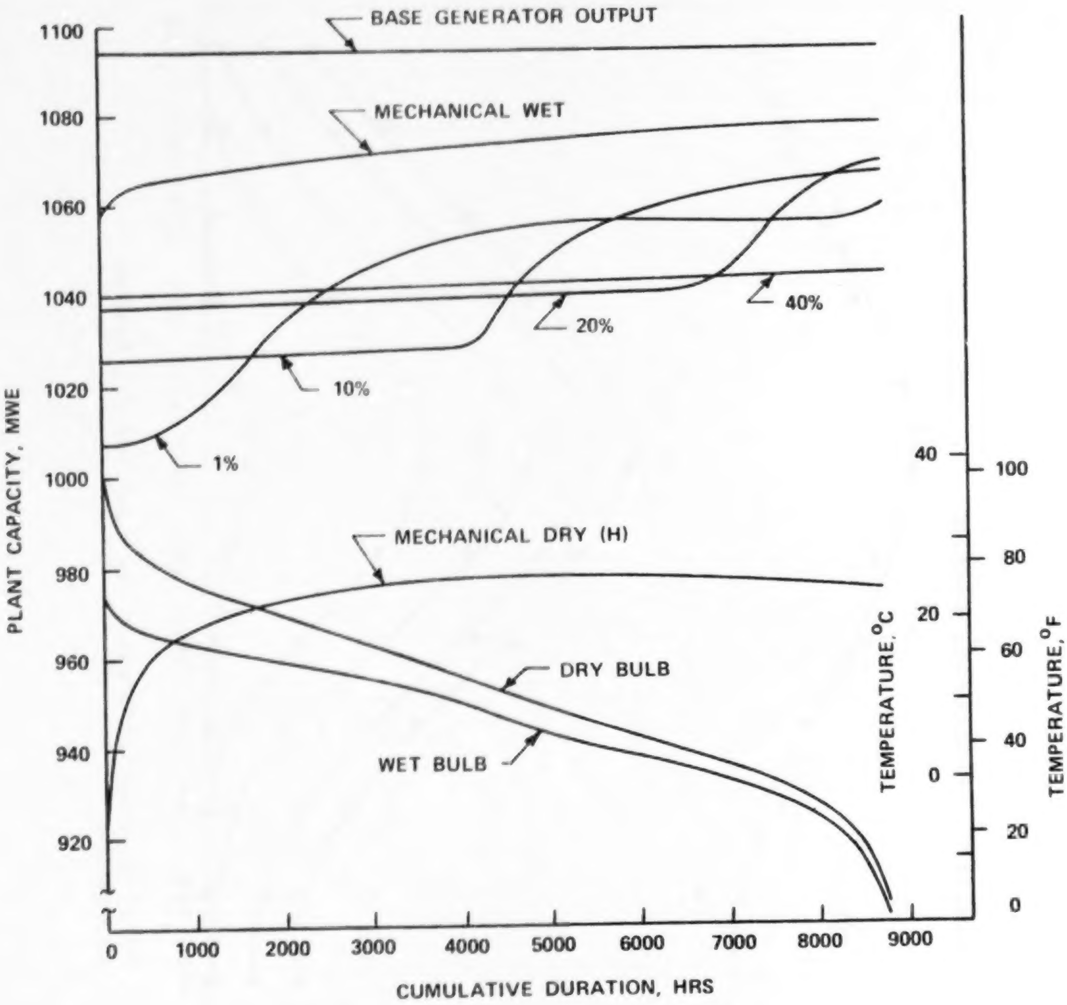


Figure 11 Net Generator Output - Middletown

392<

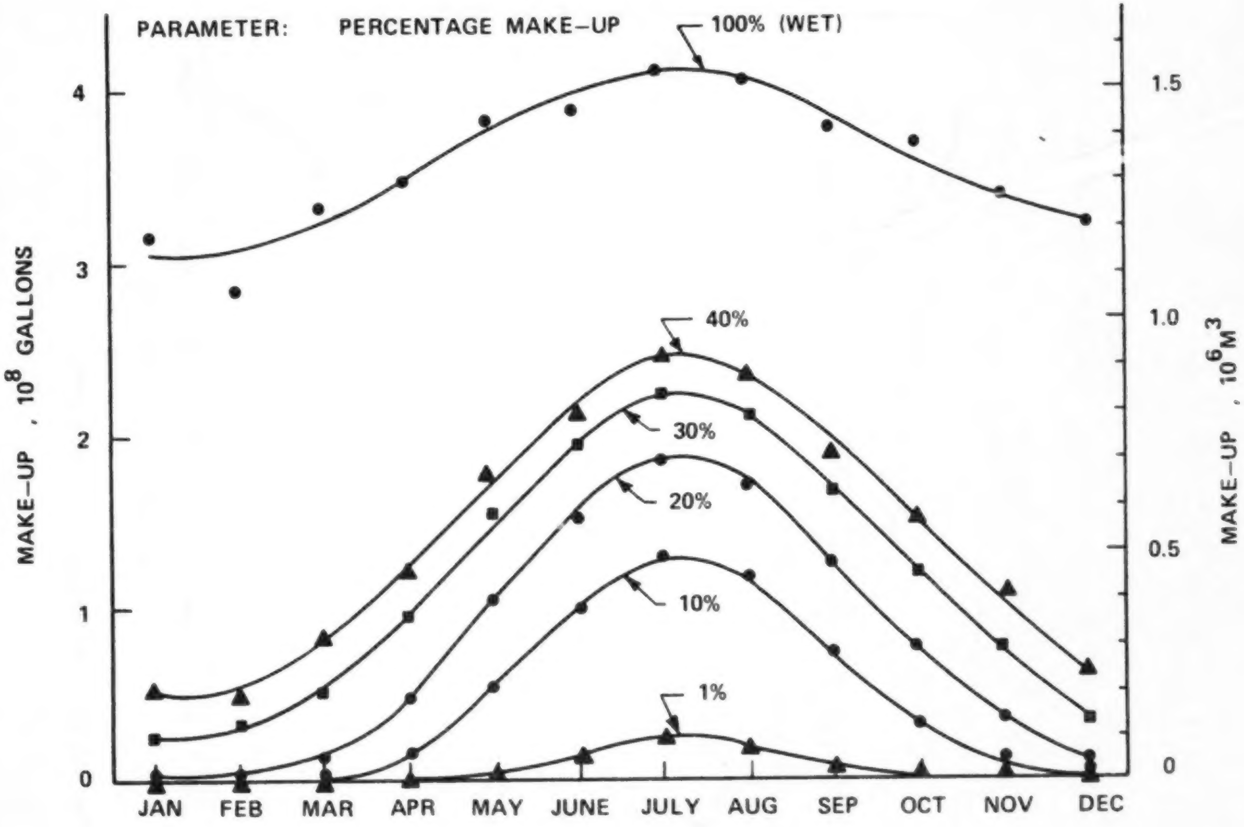


Figure 12 Total Make-up Requirement For Each Monthly Period Middletown

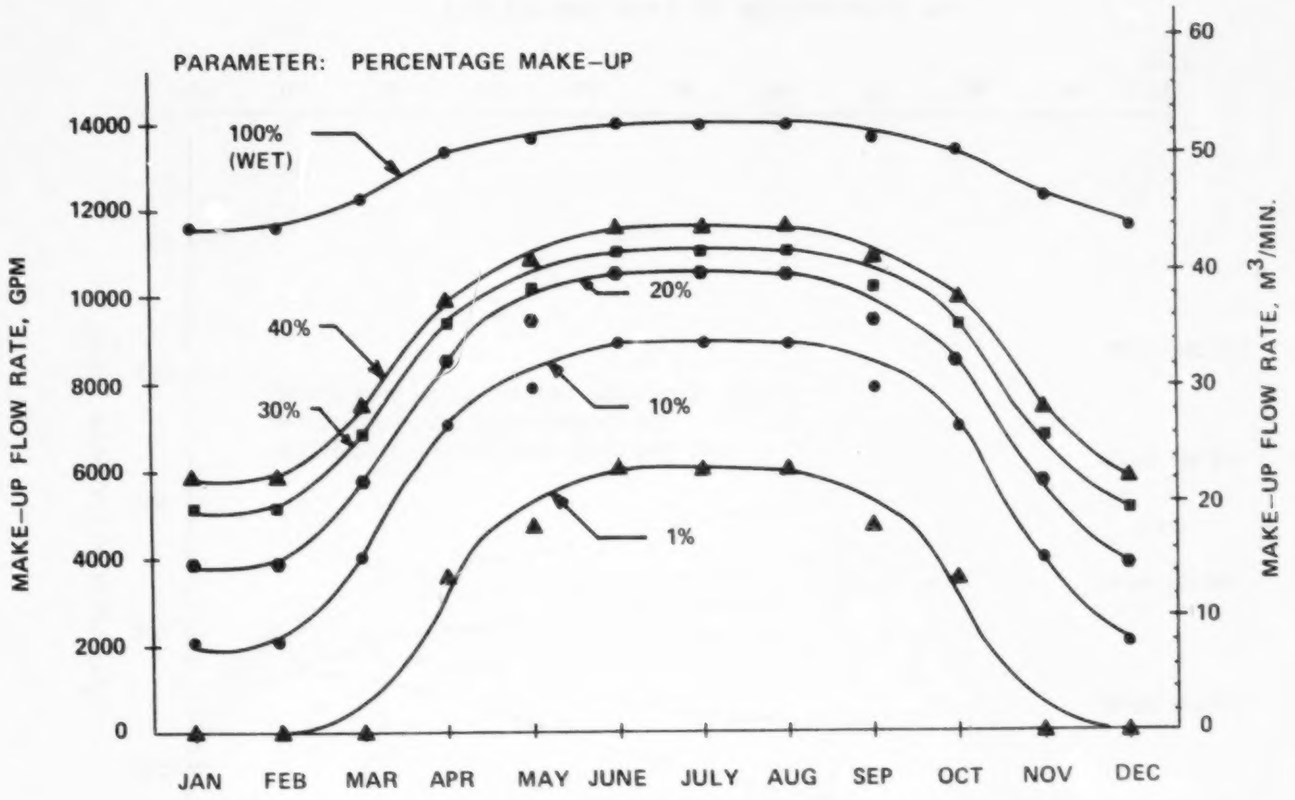


Figure 13 Maximum Make-up Flow Rate For Each Monthly Period
Middletown

394<

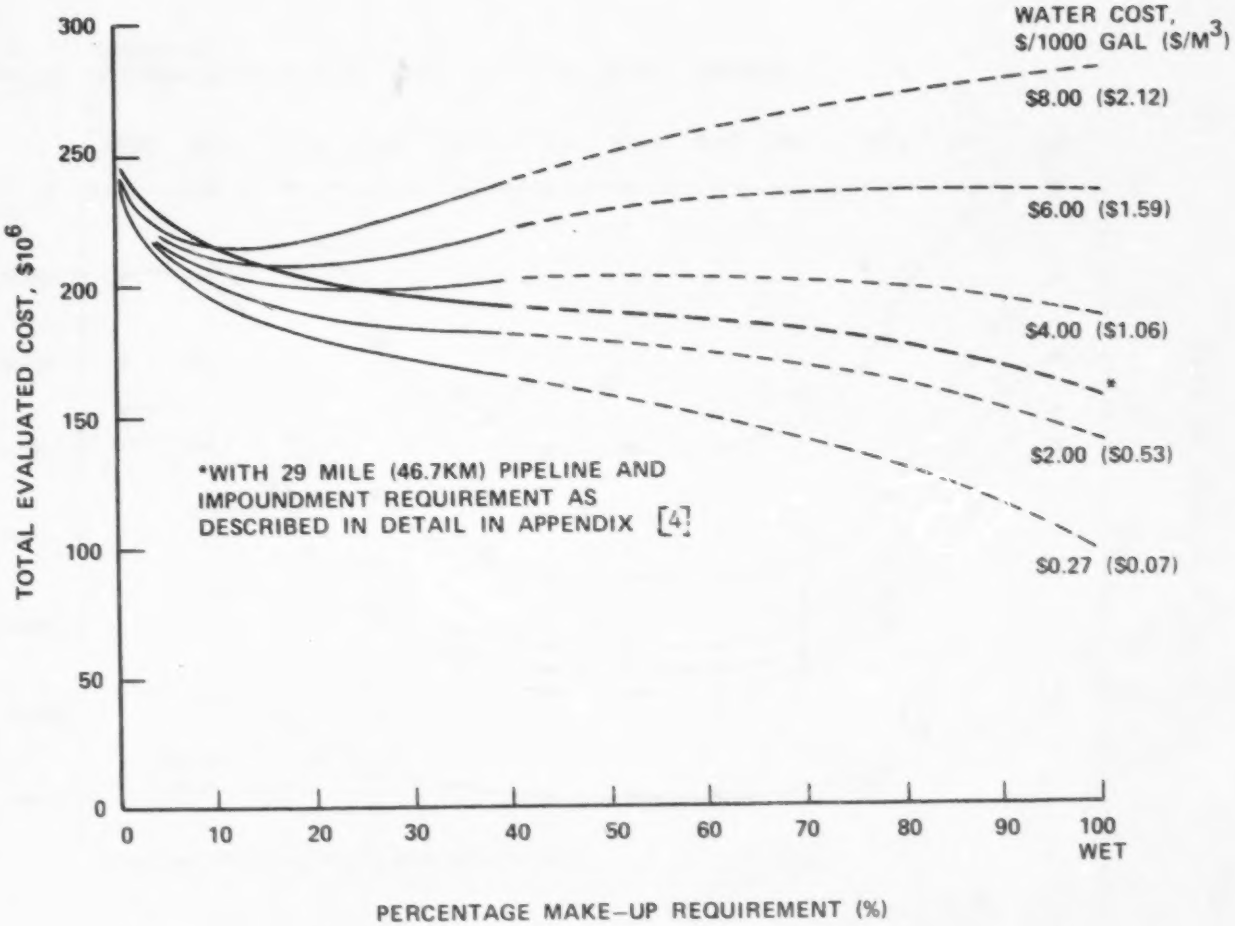


Figure 14 Impact of Water Cost On The Total Evaluated Cost Of The Optimized Wet And Wet/Dry Systems (Middletown, Mechanical Series, S1 Mode)

19-45-32

III-C-193

# OPTIMIZATION OF DRY COOLING SYSTEMS FOR 1000 MW FOSSIL FUEL POWER PLANTS

J. Fake and T. Rozenman
PFR Engineering Systems, Inc.
Marina del Rey, CA 90291

## ABSTRACT

This paper describes the methodology and the results of a study to optimize the design specifications of dry cooling systems for fossil power plants of the 1000 MWe size. The entire cooling system from the turbine flange onward, i.e. condenser, dry tower modules and recirculating system is designed employing a random combination of design variables. The optimization consists of a search for the combination of design variables which will result in the lowest incremental cost of generating electricity in the plant. For each combination of variables, the total annual capital and operating cost is determined. The capital cost is evaluated in detail taking into account all stages from procurement to complete erection and installation. The operating cost includes the equivalent capital and energy cost for auxiliaries, penalties associated with loss of capacity at high air ambient temperatures and various aspects of cooling systems operation and maintenance costs.

The results are presented in both graphical and tabular form. The results indicate that the cost of dry cooling systems are affected by all the design variables and simplified assumptions may lead to erroneous conclusions.

## GENERAL BACKGROUND

The restrictions on the use of water resources for power plant cooling in the U.S. has generated wide interest in dry cooling towers. This has served as an impetus, both in government agencies and private industry for the development of performance and economic data on these systems. The unique features and economic characteristics of dry towers have been well documented in literature. [1-5]

The major unique operating characteristic of dry cooling systems is their sensitivity to the fluctuation of the ambient temperatures. This sensitivity creates unique problems of loss in generating capacity at high ambient temperatures and freezing hazards at low temperature. The economic feature is their high capital cost - an order of magnitude higher than evaporative towers. The apriori selection of some variables such as design air temperature or fan size might restrict the optimal solution and lead to the costlier designs. An optimal design would be defined as the right combination of system operating and design variables which will produce the lowest cost of producing electricity. This combination may include subsystems, such as finned tube modules or piping that may not be optimal according to some limited thermodynamic criteria but will evolve in the design which produces the final lowest mills/kwhr.

The operation and performance of the dry tower in a power plant is unique in that a strong interaction exists among plant components. The work performed by the turbine is dependent on the cooling system's capability to absorb all the reject heat. This capability depends on the temperature difference between the saturated steam at the turbine exhaust and the ambient air. A rise in dry bulb temperature results in a corresponding rise in back pressure with lower turbine output. This decrease is also accompanied by an increase in the amount of heat that must be absorbed in the tower. Thus, a change in ambient dry bulb air temperature brings about a total change in the plant operation to a new point in which the total heat rejected from the turbine is absorbed by the ambient air flowing in the tower.

The cost of the dry tower is very much a function of its design variables. The capital cost is a function of specific module design, number of modules, construction, assembly and piping cost. The operating costs are strongly dependent on fan and pumping power and the operation of the turbine at elevated temperature which is in turn dependent on the design variables. The study of the effect of design variables on total cost of employing dry towers cannot be accomplished without accurate and detailed cost analysis of all the components of the system.

Figure 1 shows a schematic diagram of a portion of a plant equipped with a dry cooling tower. Steam from the high pressure turbine further expands in a low pressure turbine, flows to a condenser and the condensate pumped to feed water heaters for reheat. The cooling water absorbs the steam latent heat and is recooled in the cooling tower. This is the basic cooling water recirculating system that is considered in this project.

The relationship between ambient dry bulb temperature and the saturation steam temperature can be expressed as follows:

$$TS = TDRY + TAPP + TRANG + TTD \qquad (1)$$

397<

where,

TS = saturation steam temperature

TDRY = the ambient dry bulb temperature

TAPP = The difference between cold water temperature in tower and ambient dry bulb temperature and is a function of cooling tower performance.

TRANG = the temperature rise in the condenser which is identical to the cooling range in the tower.

TTD = the terminal temperature difference in the condenser between the steam saturation and the exit hot water temperature.

The ITD (initial temperature difference) is defined as

$$ITD = TAPP + TRANG \tag{2}$$

Equation (1) expresses only the characteristic of the cooling tower and is insufficient in describing the system. The complementing equation is derived from turbine heat rate - back pressure performance curve provided by the turbine manufacturer.

$$Q_{turbine} = \text{function (TS, Type of turbine, load)} \tag{3}$$

The matching of the heat rejected from the turbine expressed by Equation (3) with the heat absorbed (and rejected to the air) in the cooling tower will provide the operating point of the plant and thus the net KW output.

## TURBINE SELECTION

Two major characteristics of turbines will affect the selection of a turbine for a specific power plant:

a) Heat rate at design point

b) Shape of heat rate - back pressure curve

A turbine can be selected to provide the nominal design power output at any back pressure. However, since the heat rate increases with the specified design back pressure, more steam will be required to deliver the nominal design load. For example, a turbine designed to deliver 1000 MW at 8"Hg back pressure will require approximately 7% more steam throughput than a turbine delivering its rated 1000 MW at 3.5"Hg. The fuel cost for delivering identical power will be quite different between these two turbines. Considering a gross heat rate of 8941 BTU/Kwh for the 3.5"Hg conventional turbine, the heat rate for an 8"Hg turbine would be 9576 BTU/Kwh. Assuming a fuel cost of 1 mill/$10^3$ BTU the difference in fuel cost would be .635 mills/Kwh. For a 1000 MW plant operating 600 hr, the annual cost differential is $3.81 million. This example emphasizes the effect of heat rate at design point.

The shape of the turbine performance curve of heat rate versus back pressure is also significant in that it affect fuel economy and loss in generating capacity. The shape of this curve will be determined by the exhaust annulus area, size of last row blades, and axial mach number.

Two turbine designs were selected for this study. The first one is a modified conventional turbine which is capable of producing 1000 MW at 3.5"Hg but is allowed to operate as high as 15"Hg. The second turbine is a high back pressure turbine which is capable of producing 1000 MW at 8"Hg and is also allowed to operate up to 15"Hg. Both full load and partial load data is available from General Electric Company [6].

## CONDENSER SELECTION

The condenser component of the cooling system determines the terminal temperature difference, TTD, between the hot water in the condenser and the steam saturation temperature. Both the direct contact jet type condenser and surface condensers were studied. The jet condenser was developed specifically for dry tower application and there exist several reports that outline their design and performance characteristics [7,8]. Early reports on jet condensers quoted a 0.5°F terminal temperature difference. However, in a recent report of an installation in the Soviet Union [9], a temperature difference of 2°F was experienced. This temperature difference varied somewhat with the heat load. In the present study, the TTD in the jet condenser at full design heat load was set to 2°F and varies proportionately with the heat load.

The jet condenser will also affect the circulating water pumping power through the spray nozzle pressure drop. The design and the performance of surface condensers is a function of both the flow conditions and the mechanical construction. Tube side velocity, tube diameter and length, number of passes, etc. are all important variables. Since the reduction in back pressure is of prime importance in dry cooling systems, multiple pressure condensers are employed. The prediction of the performance of the condenser involves a procedure which is somewhat different than the design, since for a given condenser both its range and TTD will vary as a function of the heat load.

## MECHANICAL DRAFT DRY TOWER

In a mechanical draft tower the finned tubes are assembled into bundles with common inlet and exit headers. The bundles are in widths commensurate with shipping requirement, no wider than fifteen feet. The shipped bundles are assembled in the field into bays or modules which are served by one or more fans through common plenum chambers. A sufficient number of modules that satisfy the heat transfer requirement of the plant are arranged in the dry tower. Water is being circulated through the modules via a main piping system and adequate distribution manifolds. Illustrations of tower layouts are given in various publications [10,11] and not depicted here. Finned tubes come in various shapes, forms, and metallurgy [12]. The finned tubes chosen for these modules are the standard industrial 1 inch tube with 10 fins/inch. Different tube lengths were studied which varied between 40 and 80 feet. In addition the analysis was made with modules having four, five, or six rows.

The performance of the fans in dry cooling modules provides an added degree of freedom in their design and operation. The heat reject capability of a module with a fixed configuration increases with the increase in fan power. The fans employed in dry towers are large diameter axial fans. The characteristics of these fans is that they induce large air flow rate under low pressure drop - less than 1.0 in water. The fan selection for a dry tower is a major design variable and affects both the performance and capital and operating cost of the dry tower. Monroe [13] discusses the importance of fan selection on the optimization of cooling towers. In this study the largest fan diameter considered was 40 ft.

## DRY TOWER DESIGN AND RATING

The design and rating of the dry tower modules involves the calculation of tube and air side heat transfer coefficients, pressure drop and mean temperature difference. These variables are dependent on the specific module design and fan power as explained in the previous sections.

The heat reject capability of a dry tower is expressed as

$$QREJ = (N)_{mod}(ITD)(MC_p)_{mod}(P) \tag{4}$$

where

$N_{mod}$ is the number of modules

$(MC_p)_{mod}$ is the product of air flow rate and heat capacity in a module

$P$ effectiveness, ratio of air temp. rise to ITD

ITD is the initial temperature difference between the hot water and ambient air

The $(MC_p)$ is primarily dependent on fan power. The effectiveness P is a function of the number of heat transfer units, NTU, the capacity ratio R, and the pass arrangement. The NTU and R are defined as follows:

$$NTU = \frac{(U)(A)}{(MC_p)_{air}} \tag{5}$$

$$R = \frac{(MC_p)_{air}}{(MC_p)_{water}} \tag{6}$$

U is the overall heat transfer coefficient. A is the total finned tube heat transfer area. The relation between P, NTU, and R for cross flow is given graphically by Kays and London [14] and has been analytically formulated into PFR's computer program.

## DRY TOWER PIPING SYSTEM

The piping system consists of carbon steel pipes arranged above ground to provide equal water flow to each tube module. The main supply and return lines are designed with appropriate valving to bypass the dry cooling towers and to isolate the circulating pumps and water recovery turbines. In addition, storage tanks with fill pumps, valving and fill piping are included to facilitate easy draining or filling of the dry tower. All piping includes expansion joints to relieve any thermal growth. In general, all pipes are standard wall and designed for a water velocity between 8 - 12 ft/sec.

As much shop work as possible is done in order to reduce the amount of expensive field work that is needed. Cooling water is pumped from the main condenser to the dry tower which is located 500 feet away. The supply line enters perpendicularly at the middle of the tower and branches in both directions to supply water along the entire length of the tower. At each module (3 tube bundles with a common header) a feeder line rises to a bay distribution manifold. The feeder lines are adequately valved in order to shut off water flow to the entire modules. The module distribution manifold then distributes the water to the inlet headers of the 3 tube bundles. In order to keep piping costs at a minimum the size of the supply and return lines reduce in size as the water flow rate decreases along the length of the tower. The return scheme is identical to the supply scheme.

## Piping Pressure Drop

The pressure drop of the piping system is calculated by determining the loss through each section of the piping, taking into account losses from valves and elbows. By changing the supply and return line pipe diameter to keep the water velocity nearly constant, there will be no momentum losses or maldistribution in the system. The total pumping head depends on the type of condenser. For a surface condenser the pumping head is the sum of the tube bundle, supply and return piping, and condenser tube losses.

The major constraint is to ensure that the operating pressure for the condenser does not exceed the limit of the waterbox design pressure.

In a direct contact condenser the cooling water comes into direct contact with the steam turbine exhaust. Thus it is important not to contaminate the cooling water by allowing air to leak into the tube modules. To protect against this an hydraulic head recovery turbine is placed in the return piping. This will elevate the pressure of the system so that the tube modules are 3 feet above atmospheric pressure. The pump must overcome the head difference between the top of the condenser where the water is sprayed and the bottom of the condenser where the liquid water level is. In addition the pump must overcome the spray nozzle drop, the tube bundle loss, and the return and supply piping loss.

Table 1 demonstrates representative differences in pumping heads for the different types of condenser.

## DRY COOLING TOWER STRUCTURE

The supporting structure for the dry cooling tower is a steel braced system with bracings in all three planes. In addition to the transverse, horizontal and longitudinal steel bracing system a network of I-beams and columns form the main structure which supports the weight. The foundations for these columns consist of three foot deep reinforced concrete. Proper site preparation is performed which includes three foot high excavation, compaction, and grading. The site is cleared and prepared for an additional 30 feet on both sides of the tower and a paved road is constructed down one side for easy accessibility to the entire tower. The structure is designed for Seismic Zone 3 with a roof live load of 40 pounds per square foot and a wind loading of 35 pounds per square foot. Thus, the tower structure would satisfy building codes almost anywhere in the United States.

## ECONOMIC MODEL AND OPTIMIZATION

Much work has been done in trying to optimize some the design of large, mechanically induced cooling towers. Some of these studies use approximate relations for the heat transfer process in the tower and simplified generalized cost functions. Furthermore the optimization was carried out by varying only one, or at most two, variables while fixing the other variables arbitrarily. Rozenman and Pundyk [15] discuss these points in detail.

In this work all independent variables that define the cooling tower and affect the design and operating conditions are included in the optimization scheme. These are:

a. Design ambient dry air temperature
b. ITD of the tower
c. TTD of the condenser
d. Cooling water temperature range
e. Overall number of modules
f. Fan horsepower
g. Tube length, number of rows and number of passes

The study is made on a 1000 MW fossil fuel plant, 2400 Psig, 1000°F/1000°F, located in preassigned geographical areas. Two alternate tubine designs are chosen for the plant -- the high back pressure turbine and the modified conventional turbine.

The plant is a summer peaking base load plant with an average capacity factor of 0.75. The capacity is distributed over the year as follows:

100% load - July, August, September

75% load - the rest of the year

Shut-down - April

## Cooling System Capital Cost

The capital cost of the cooling system includes equipment and labor cost for the total cooling system from the turbine flange onward. Because of the logistics involved with the various components of the tower and expenses incurred in field installation, the construction is based on a modular basis in which shop fabrication is maximized. The cost breakdown includes the following:

* Cost of fabricated finned tube bundles with proper headers, nozzles, and support plates prepared for shipping.
* Cost of fabricated sections for the plenum and recovery stack. These sections are shipped to the construction site for installation.
* Cost of the fans, fan motors, gearboxes.
* Shipping cost of the above items.
* Cost of support structure. The cost includes the structural steel fabrication and erection. Site preparation, foundation, walkways and ladders, field and shop labor, and miscellaneous painting.
* Erection cost of modules and fans. The shipped bundles are set and aligned on the support stucture and combined together with the plenum chamber. The fans, motors and gearboxes are installed, the recovery stacks are installed, and the fans are balanced and tested. All labor and material cost as well as support crane costs are included.
* Pumping system. Cost of circulating water pumps and drives, water recovery turbines, pump and water recovery foundation.
* Cost of electrical substation and cabling. Labor and material cost, conduit and cable for connecting the power to the fan motors and pumps. Also included in incremental transformer and station service cost.
* Piping system. Cost of material and labor for main supply and return piping. cost of material and labor for module inlet and outlet manifold and feeder line. Cost of fill and bypass lines, valving, expansion joints, controls, and storage tanks.
* Cost of surface condenser and installation.

The annualized cost for the cooling system investment is equal to the capital cost multiplied by the fixed charge rate.

## Cooling System Penalties and Operating Costs

Capacity penalty is the cost of building the capability to produce the power that is lost due to the poor performance of dry cooling towers during hot ambient conditions. The most simple method is to erect a gas turbine on site to provide the power during hot peaking conditions. Another method is to expand the plant under consideration to supply the loss in power. This study uses a cost of \$100./KW for installed gas turbine capacity and \$500./KW for installed capacity of a new plant.

Another capital expense areises from the fact that steam turbines for dry cooling towers are designed with slightly more steam flow than conventional turbines. The steam supply system could be expanded for a modified conventional turbine at a cost of \$750,000., and for the high back pressure turbine 5.4 million dollars would be necessary.

Energy penalty is the cost of producing that power that is lost due to poor dry cooling tower performance. It was assumed that gas turbine power would cost 40 mills/kw-hr, but at ambient temperatures below 82°F power could be bought from the system at 20 mills/kw-hr. If the energy penalty is assessed on building the plant slightly larger, a cost of 10 mills/kw-hr is used regardless of ambient temperature.

Special consideration must be given to penalties due to cooling system auxiliaries. This pertains to the power drawn by the fans and the recirculating pumps. This auxiliary power reduces the power available at the bus bar for the load demand and its costs are considered as additional penalty cost. There exist two ways to supplement the auxiliary power required to run the fans and the circulating pumps. The first way is to consider the auxiliary power to be a penalty loss similar to loss of capability at high temperature. Thus, draw the auxiliary power from the same source as the loss in capability at high temperatures with the corresponding charges for capacity and penalty. The second way is to consider that the auxiliary power requirement would be of long duration and would be required even at low ambient temperatures. Expand the base plant capacity to supply the required auxiliaries. In such a case the auxiliaries capital and energy charges will use base plant cost factors.

There exist several considerations unique to dry tower application which will influence the choice of power for cooling system auxiliaries. If the yearly load demand profile is such

405<

that the plant will operate in part load mode for a fraction of the year, the auxiliary power can be generated without plant expansion by simply overfiring the existing plant. The cost penalty for this case will not include expanded plant capacity capital cost but incremental fuel cost that is charged for generating the auxiliary power.

Another factor which influences the choice of the source for auxiliaries is the potential for fan control. In dry cooled systems approximately 75% of the auxiliary power requirement is due to the fans and the other 25% is the water pumping power. Below a back pressure of about 5 inHg the heat rate curve for a high back pressure turbine is almost flat and little gain in power output is achieved with the reduction in back pressure. Thus it would be more economical to maintain a constant back pressure and reduce fan power as the ambient temperature is reduced. The constant back pressure is reached beyond which the extra turbine power from a decrease in back pressure is offset by the reduction of the controlled auxiliary fan power. A typical curve of fan controlled power reduction as a function of ambient temperature is given in Figure 2.

The above behaviour would indicate that considering the source for auxiliary power requirement as identical to the source for loss in capacity at high ambient (i.e. gas turbines) has economic merits by saving the cost for incremental base plant capacity.

## Optimization Methodology

A computer program was written to optimize the design of dry cooling tower systems. The steps in the optimization code are as follows:

1) Design the cooling system, i.e. dry tower, circulating system and condenser on the basis of a combination of design variables.

2) Calculate capital cost of the system. All components of the entire system are accurately priced.

3) Determine plant performance with the changes in annual ambient temperatures.

4) Calculate capital and energy cost for loss in generating capacity and cooling system auxiliaries. Employ fan control and extra firing when advantageous. Calculate total fuel cost.

5) Determine total incremental bus bar cost of the cooling system.

6) Employ the box multicomponent optimization search scheme to generate a new set of design variables that will lead to lower cost.

7) Stop when the combination of variables that will result in lowest cost has been found.

8) Print the optimal results.

The first step involves the selection of random combinations of design variables consisting of heat load, ITD, range, TTD, tube length, and number of modules. The program iterates to find the right approach velocity which will satisfy the heat transfer characteristics of the modules. A suitable fan design is selected and total fan horsepower is calculated.

The second step involves the design of the condenser, interconnecting piping, pumping horsepower, pumps, storage tanks controls and valves, and all other auxiliary equipment of the cooling system. The capital cost of all the components is then evaluated as well as the labor and material for shipping, structure and foundation, erection, and construction and electrical work.

The third step involves the evaluation of the plant performance with the annual changes in the ambient temperatures. The highest ambient temperature for penalty calculations is determined drom the annual probability curve. For each combination of ambient temperatures and the time occurrence (number of hours) the program calculates plant performance by matching heat reject from tower with heat load of the turbine. Heat transfer calculations are performed to find the turbine back pressure for each given ambient temperature. At each ambient temperature a check is made whether fan control is economical and whether the demanded load is less than 100%. If demanded load is full 100% the energy penalty is calculated. If load is below 100%, a search is made for a turbine operating point which produces the demanded load plus auxiliary power. The fuel consumption energy penalty and replacement capacity are all calculated.

Upon evaluating the performance over the entire year the program calculates and sums the fuel cost, energy penalty cost, replacement capacity cost, capital and operating costs, the total annual cost and the total incremental bus-bar cost of the cooling system. The program then utilizes the 'Box' multicomponent optimization search scheme |16| and generates a new set of independent variables and repeats the entire process. The calculation stops when a combination of design variables is found which leads to the lowest cost.

As was evident in the analysis, there exist many combinations of the design variables which will result in a cooling system with identical total annual cost. Since the cost is a function of six variables, it cannot be represented simply as a graph on a two-dimensional plot. The effect of design variables on the cost was investigated by tabulating all the cost points for the combinations of all variables. No graphs ca be plotted since the functional variation on a two-dimensional plot is not easily discernible.

Figure 3 shows how the annual cost may vary with the ITD. The points on the figures are the annual cooling systems cost designed with a random combination of design variables. Each point represents the annual cost of the cooling system with different ITD, range, fan horsepower, number of modules, TTD, and design ambient temperature. No discernible curves can be plotted through the points. For any given fixed ITD, the annual cost may vary by about three to four million dollars (vertical distance between high and low points) depending on the combination of design variables. It is evident that the points converge to a domain of ITD's in which the cost reaches minimum but no single point is the absolute minimum - there exist several points with different ITD and identical cost. This indicates that other design variables such as fan horsepower and range may have compensating effects on the total annual cost.

Figure 4 shows the variation of annual cost with range/ITD for the Phoenix site. The ITD was kept fixed at 30°F. Large variations in cost are evident. The lowest point tends to converge between ratios of 0.4 and 0.6. However, for each fixed range/ITD ratio the price can vary by over a million dollars (vertical distance on the graphs). This indicates that no specific optimum range/ITD ratio exists but is a function of the other independent design variables.

Figure 5 shows the effect of auxiliary power-pumping and fan power on the total annual cost. Wide variation of cost with auxiliary power is evident with no specific trend. Figure 5 is for a Phoenix site using gas turbine for supplementing loss in capacity (capacity cost 100$/kw, energy cost 40/20 mills/kwh). The figure shows that the total annual cost is sensitive to the auxiliary power - deviation of ±3 MW from the lowest point result in an increase of about 0.5 million dollars.

Figure 6 shows the variations in total annual cost for various tube lengths with the ITD fixed in a range of 41°-43°F. Variations of up to three million dollars are evident in the cost. However, the lowest cost was obtained with a module using 80 feet long tubes.

JE 408<

Two major conclusions can be drawn from the above results:

a. The cost is dependent on all the variables of the cooling system. No single variable is dominating the cost and setting some variables as fixed values can lead to non-optimal results.

b. There exist several combinations of design variables which will result in the lowest cost. No unique combination exists since some variables tend to have compensatory effects on the cost.

The optimal combinations will lead to the lowest annual cost. The next section describes the results and parametric analysis using the optimal results.

## EFFECT OF SITE ON COST OF DRY COOLING

Table 2 shows the cost summary of dry cooling systems employed for power plants located in five sites within the continental USA. This data represents optimal designs. Design and cost information are grouped in the table for easy identification and interpretation of the results. The tube configuration of the modules consists of six rows with two passes (6R2P) and are 80 feet long. The highest ambient temperature used for penalty assessment was selected as the temperature that is not exceeded 29 hours during the summer.

Table 2 shows the stron effect which the location has on the cost of the dry cooling system. The annual cost of a dry cooling system located in Burlington, Vermont, is 7.5 million dollars cheaper than a system located in Phoenix, Arizona. This is evident from the different ambient weather conditions at the two sites. The Phoenix site has a maximum ambient temperature (occurring 29 hours in the summer) of 109.5°F, whereas Burlington's maximum temperature is only 88.2°F (occurring 29 hours in the summer). Furthermore, the Phoenix site has over 2760 hours of temperatures above 82°F as compared to 176 hours in Burlington. Both the maximum temperature of the site and the area under the annual probability temperature curve affect the cost of the dry tower.

## EFFECT OF TURBINE TYPE

Table 3 shows the results of the analysis for plants employing either the high backpressure or the modified conventional turbine. Both the Casper and the Phoenix sites were studied. The results of Table 3 were computed with a fuel cost of $0.75/ MMBTU. Table 3 shows that for this fuel cost the use of a high back pressure turbine results in a cheaper incremental cost for the dry tower cooling system. The modified conventional turbine uses much less fuel, i.e. the incremental fuel cost is much lower. However, this savings is nullified by the higher capital cost and higher energy and capacity penalties. The difference in dry tower cost for the two turbines for the same site is primarily a function of the fuel cost.

Table 4 shows the total cost of the dry tower systems for both alternate turbines as a function of fuel cost for the Casper site. As the fuel cost increases fuel savings begin to play a more dominant role and the modified conventional turbine becomes cheaper than the high back pressure turbine. At a fuel cost of $1.5/MMBTU, the capital cost and energy penalties are still higher for a modified conventional turbine but the incremental fuel cost is about $4.0 million lower than the high back pressure turbine. The tabulated results of Tables 3 and 4 are shown graphically in Figure 7 which shows the effect of unit fuel cost on dry tower systems for the two turbines. Figure 11 shows that for the Casper site the break-even fuel cost is slightly over $1.00/MMBTU.

The high back pressure turbines seem quite attractive for hot climates and sites with low fuel costs. The capital cost of the high back pressure turbine was assumed to be the same as the cost of a conventional turbine. However, the cost of design modification required to accomodate the operation of the turbine at high back end temperatures may outweigh the advantages of smaller energy penalties.

## EFFECT OF CONDENSER

Both surface condensers and direct contact condensers were studied for the Casper site with either a modified conventional turbine or a high back pressure turbine. Table 5 indicates that using a surface condenser would cost approximately 200,000 dollars/year above the cost of a jet condenser. Basically, this is due to the fact that a surface condenser has about a 3°F higher TTD than a direct contact condenser and requires an equivalently lower ITD tower design. Thus, the capital costs are higher for a system with a surface condenser. If a modified conventional turbine is used this difference in the TTD will also result in higher penalties for the design with the surface condenser. This is not necessarily so for a high back pressure turbine since its heat rate curve is much flatter and a 3°F rise in saturation temperature is not quite as significant.

Another noteworthy observation about Table 5 is that the incremental fuel cost is lower for the system with a surface condenser. This results from the higher pumping power required for a direct contact system (on the order of 2.5 MW).

Additional fuel must be consumed to provide power to run the pumps. This difference is especially significant at part loads when fan control occurs. Therefore, an increase in the fuel cost would most probably make the systems with surface condensers cheaper.

## EFFECT OF TUBE CONFIGURATION

The effect of the number of rows and passes of the dry cooling tower tube modules on the total annual cost is surprisingly small. The conclusions on tube configuration that can be drawn are valid for the fuel cost, fixed charge rate and other variables that were used. Different fuel cost, for example, could produce different results. It seems that the savings in pumping costs for one pass designs is outweighed by the increased piping costs and reduced heat transfer capabilities. Of the two pass designs, the number of rows is not a major consideration. Six row designs are probably more desirable since they require less plot area and less numbers of fans and modules. Above six rows standard size fans can no longer provide the necessary air flow and schemes involving large diameter fans or sharing fans between bays would have to be employed.

## EFFECT OF TUBE LENGTH

The effect of tube length was studied by choosing three different situations and optimizing the design using 40, 50, 70, and 80 foot tubes. The general trend was a decrease in total annual cost with an increase in tube length. Tube lengths above 80 feet were not sutdied because of uncertainties in shipping procedures. In all three cases the 70 foot design was slightly more expensive than the 60 foot design. This was due to the fact that shipping costs are higher for lengths greater than 60 feet and a single fan per bay can no longer provide the required air flow. Thus two fans per bay are required which increases the module cost and uses more auxiliary horsepower. Eighty foot tubes provide the economy of size over smaller designs and permit more efficient fan design optimization due to the larger fans that can be used.

Table 6 demonstrates these effects. For the cases studied, it is evident tat 80 foot tubes are more attractive. The fact that they have an increased pressure drop is insignificant compared to the high costs of modules and the amount of power required for the fans. Longer tubes could be studied to examine whether their increased handling and shipping costs are offset by their savings in piping costs, etc.

## ACKNOWLEDGEMENT

This paper resulted from work supported by the U.S. Environmental Protection Agency, Thermal Pollution Branch, Corvallis, Oregon. We want to thank Mr. J. P. Chasse for his constructive guidance throughout the various phases of this project.

## REFERENCES

1. Rossie, J. and E. A. Cecil, "Research on Dry-Type Cooling Towers for Thermal Electric Generation", Parts I, II, EPA Report #16130, EES, 11/70.

2. Heat Sink Design and Cost Study for Fossil and Nuclear Power Plants, WASH-1360, United Engineers and Constructors Inc., Philadelphia, PA., December, 1974.

3. J. F. Sebald, Report on Economics of LWR and HTGR Nuclear Power Plants with Evaporative and Dry Cooling Systems Sited in the United States, GAI Report No. 1869, Gilbert Associates, Inc., Reading, Pa., June, 1975.

4. Andeen, B. R. and L. R. Glicksman, "Dry Cooling Towers for Power Plants", Report #DSR73047-1, Dept. of Mechanical Engineers, M.I.T.

5. Larinoff, M. W., "Dry Cooling Tower Power Plant Design Specifications and Performance Characteristics", ASME publication, "Dry and Wet/Dry Cooling Towers for Power Plants".

6. General Electric Co., Private Communications.

7. Heeren and Holly, "Air Cooling for Condensation and Exhaust Heat Rejection in Large Generating Stations", American Power Conference, April, 1970, Chicago.

8. Heller, L., "Wet/Dry Hybrid Condensing System", in Dry and Wet/Dry Cooling Towers for Power Plants, manual published by A.S.M.E., New York, p. 85, 1973.

9. Report of the U.S. Dry and Dry/Wet Cooling Tower Delegation Visit to the Union of Soviet Socialist Republics, May 26 to June 7, 1975.

10. Smith, E. C., and M. W. Larinoff, Power Plant Siting, Performance and Economics with Dry Cooling Tower Systems, American Power Conference, April, 1970.

11. "Dry Cooling Towers for Large Power Installations", The Marley Company, 1972.

12. "Heat Transfer and Pressure Drop Characteristics of Dry Tower Extended Surfaces", Parts I, II, prepared by PFR Engineering Systems for the Dry Cooling Tower Program, Battelle Northwest Laboratores, March, 1976.

13. Monroe, R. C., "Fans Key to Optimum Cooling Tower Design", Oil and Gas Journal, May 27, 1974.

14. Kays and London, "Compact Heat Exchangers", 2nd Edition, McGraw-Hill Book Company, 1964.

15. Rozenman, T. and Pundyk, J., "Design Considerations in the Optimization of Dry Cooling Towers".

16. Box, M. J., "A New Method of Constrained Optimization and a Comparison with Other Methods", Computer Journal 8, p. 42-52, 1965.

## TABLE 1. TYPICAL PERMANENT HYDRAULIC PRESSURE LOSSES

All losses in Feet of Water

| | Surface Condenser | Direct Contact with Recovery Turbine | Direct Contact Without Recovery Turbine |
|---|---|---|---|
| Supply Lines and Distribution Piping | 6.5 | 6.5 | 6.5 |
| Tube Bundle | 25.0 | 25.0 | 25.0 |
| Return Piping | 6.5 | 6.5 | 6.5 |
| Condenser Head | --- | 14.0 | 14.0 |
| Condenser Spray Nozzles | --- | 13.0 | 13.0 |
| Condenser Tubes | 17.0 | --- | --- |
| Recovery Turbine or Throttling Valve | --- | 75.0 | 75.0 |
| Total Pumping Head | 55.0 | 140.0 | 140.0 |
| Head Recovered by Recovery Turbine | --- | 60.0 | --- |
| Net Pumping Head Penalty | 55.0 | 80.0 | 140.0 |

415<

JF

## TABLE 2 - EFFECT OF SITE ON TOTAL ANNUAL COST

SITE = ----
TURBINE TYPE = MOD.CONV.
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = .75
CAPACITY COST ($/KW) = 100
ENERGY COST (MILLS/KW-HR) = 40/20

TUBE CONFIGURATION = 6R2P
CONDENSER TYPE = SURFACE
TUBE LENGTH (FT.) = 80
CAPACITY FACTOR = .75
SUMMER HRS NOT EXCEEDED = 29
HOURS ABOVE 82°F AMBIENT = ----

NOTE: ALL COSTS ARE ANNUALIZED

| | | | | | |
|---|---|---|---|---|---|
| TOTAL COST ($x1000) | 20522 | 15612 | 14869 | 14593 | 12817 |
| SITE | PHOENIX | ATLANTA | CASPER | BISMARCK | BURLINGTON |
| HOURS ABOVE 82°F AMBIENT | 2760 | 783 | 440 | 415 | 176 |
| AMBIENT EXCEEDED BY 29 HRS (°F) | 109.5 | 95.3 | 93.1 | 96.1 | 88.2 |
| MODULE COST ($x1000) | 5594 | 5370 | 4961 | 4846 | 4268 |
| PIPING COST ($x1000) | 1964 | 1778 | 1661 | 1652 | 1420 |
| CONDENSER COST ($x1000) | 990 | 854 | 828 | 844 | 730 |
| CAPACITY PENALTY ($x1000) | 2293 | 1644 | 1828 | 1872 | 1798 |
| ENERGY PENALTY ($x1000) | 6612 | 3184 | 3014 | 2815 | 2181 |
| INCREMENTAL FUEL COST ($x1000) | 1316 | 1106 | 968 | 959 | 944 |
| ANNUAL FUEL COST ($x1000) | 45541 | 45331 | 45192 | 45184 | 45169 |
| NUMBER OF MODULES | 80 | 76 | 72 | 68 | 60 |
| TOTAL FAN MW | 21 | 18 | 18 | 21 | 17 |
| TOTAL AUXILIARY MW | 29.0 | 24.7 | 24.4 | 28.1 | 22.4 |
| MAX BACK PRESSURE (in.Hga) | 9.7 | 7.5 | 8.2 | 8.1 | 8.2 |
| MAX LOSS IN GENERATION (MW) | 114.7 | 82.2 | 91.4 | 93.6 | 89.9 |
| TTD (°F) | 5.1 | 5.0 | 5.0 | 5.0 | 5.2 |
| ITD (°F) | 43.9 | 48.4 | 53.9 | 50.6 | 58.8 |
| RANGE (°F) | 21 | 24 | 26 | 25 | 31 |

## TABLE 3 - EFFECT OF TURBINE TYPE

SITE = ----
TURBINE TYPE = ----
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = .75
CAPACITY COST ($/KW) = 100
ENERGY COST (MILLS/KW-HR) = 40/20

TUBE CONFIGURATION = 6R2P
CONDENSER TYPE = SURFACE
TUBE LENGTH (FT.) = 80
CAPACITY FACTOR = .75
SUMMER HRS NOT EXCEEDED = 29
HOURS ABOVE 82°F AMBIENT = --

NOTE: ALL COSTS ARE ANNUALIZED

| TOTAL COST ($x1000) | 14255 | 14869 | 17193 | 20522 |
|---|---|---|---|---|
| TURBINE TYPE | HIGH B.P. | MOD.CONV. | HIGH B.P. | MOD.CONV. |
| SITE | CASPER | CASPER | PHOENIX | PHOENIX |
| MODULE COST ($x1000) | 4645 | 4961 | 4660 | 5594 |
| PIPING COST ($x1000) | 1465 | 1661 | 1684 | 1964 |
| CONDENSER COST ($x1000) | 717 | 828 | 875 | 990 |
| CAPACITY PENALTY ($x1000) | 833 | 1828 | 1268 | 2293 |
| ENERGY PENALTY ($x1000) | 1059 | 3014 | 2930 | 6612 |
| INCREMENTAL FUEL COST ($x1000) | 2963 | 968 | 3146 | 1316 |
| ANNUAL FUEL COST ($x1000) | 47188 | 45192 | 47371 | 45541 |
| NUMBER OF MODULES | 68 | 72 | 68 | 80 |
| TOTAL FAN MW | 18 | 18 | 19 | 21 |
| TOTAL AUXILIARY MW | 23.1 | 24.4 | 27.1 | 29.0 |
| MAX BACK PRESSURE (in.Hga) | 10.4 | 8.2 | 12.4 | 9.7 |
| MAX LOSS IN GENERATION (MW) | 41.7 | 91.4 | 63.4 | 114.7 |
| TTD (°F) | 5.7 | 5.0 | 5.1 | 5.1 |
| ITD (°F) | 64.3 | 53.9 | 55.9 | 43.9 |
| RANGE (°F) | 33 | 26 | 25 | 21 |
| HOURS ABOVE 82°F AMBIENT | 440 | 440 | 2760 | 2760 |

417<
JF

TABLE 4 - EFFECT OF TURBINE TYPE

SITE = CASPER
TURBINE TYPE = ----
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = ----
CAPACITY COST ($/KW) = 100
ENERGY COST (MILLS/KW-HR) = 40/20

TUBE CONFIGURATION = 6R2P
CONDENSER TYPE = SURFACE
TUBE LENGTH (FT.) = 80
CAPACITY FACTOR = .75
SUMMER HRS NOT EXCEEDED = 29
HOURS ABOVE 82°F AMBIENT = 440

NOTE: ALL COSTS ARE ANNUALIZED

| TOTAL COST ($x1000) | 17165 | 15936 | 15198 | 15236 |
|---|---|---|---|---|
| TURBINE TYPE | HIGH B.P. | MOD.CONV. | HIGH B.P. | MOD.CONV. |
| FUEL COST ($/MMBTU) | 1.50 | 1.50 | 1.00 | 1.00 |
| MODULE COST ($x1000) | 4611 | 4812 | 4359 | 5026 |
| PIPING COST ($x1000) | 1462 | 1620 | 1454 | 1739 |
| CONDENSER COST ($x1000) | 730 | 815 | 722 | 879 |
| CAPACITY PENALTY ($x1000) | 858 | 1918 | 977 | 1759 |
| ENERGY PENALTY ($x1000) | 1013 | 3194 | 1192 | 2871 |
| INCREMENTAL FUEL COST ($x1000) | 5931 | 1950 | 3965 | 1328 |
| ANNUAL FUEL COST ($x1000) | 94381 | 90400 | 62932 | 60294 |
| NUMBER OF MODULES | 68 | 68 | 64 | 72 |
| TOTAL FAN MW | 14 | 17 | 15 | 18 |
| TOTAL AUXILIARY MW | 19.9 | 23.6 | 20.7 | 25.3 |
| MAX BACK PRESSURE (in.Hga) | 10.9 | 8.6 | 11.5 | 7.9 |
| MAX LOSS IN GENERATION (MW) | 42.9 | 95.9 | 48.8 | 88.0 |
| TTD (°F) | 5.2 | 5.2 | 5.3 | 5.1 |
| ITD (°F) | 66.6 | 55.5 | 68.9 | 52.2 |
| RANGE (°F) | 33 | 26 | 34 | 23 |

## TABLE 5 - EFFECT OF CONDENSER TYPE

SITE = CASPER
TURBINE TYPE = ---
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = .75
CAPACITY COST ($/KW) = 100
ENERGY COST (MILLS/KW-HR) = 40/20

TUBE CONFIGURATION = 6R2P
CONDENSER TYPE = ----
TUBE LENGTH (FT.) = 80
CAPACITY FACTOR = .75
SUMMER HRS NOT EXCEEDED = 29
HOURS ABOVE 82°F AMBIENT = 440

NOTE: ALL COSTS ARE ANNUALIZED

| | | | | |
|---|---|---|---|---|
| TOTAL COST ($x1000) | 14869 | 14600 | 14255 | 14072 |
| CONDENSER TYPE | SURFACE | JET | SURFACE | JET |
| TURBINE TYPE | MOD.CONV. | MOD.CONV. | HIGH B.P. | HIGH B.P. |
| MODULE COST ($x1000) | 4961 | 4896 | 4645 | 4302 |
| PIPING COST ($x1000) | 1661 | 1675 | 1465 | 1450 |
| CONDENSER COST ($x1000) | 828 | 721 | 717 | 738 |
| CAPACITY PENALTY ($x1000) | 1828 | 1751 | 833 | 834 |
| ENERGY PENALTY ($x1000) | 3014 | 2856 | 1059 | 1109 |
| INCREMENTAL FUEL COST ($x1000) | 968 | 1051 | 2963 | 3056 |
| ANNUAL FUEL COST ($x1000) | 45192 | 45276 | 47188 | 47281 |
| NUMBER OF MODULES | 72 | 72 | 68 | 64 |
| TOTAL FAN MW | 18 | 17 | 18 | 17 |
| TOTAL AUXILIARY MW | 24.4 | 26.3 | 23.1 | 24.0 |
| MAX BACK PRESSURE (in.Hga) | 8.2 | 7.7 | 10.4 | 10.3 |
| MAX LOSS IN GENERATION (MW) | 91.4 | 87.6 | 41.7 | 41.7 |
| TTD (°F) | 5.0 | 2.0 | 5.7 | 2.0 |
| ITD (°F) | 53.9 | 57.3 | 64.3 | 67.1 |
| RANGE (°F) | 26 | 27 | 33 | 32 |

## TABLE 6 -- EFFECT OF TUBE LENGTH

SITE = PHOENIX
TURBINE TYPE = MOD.CONV.
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = .75
CAPACITY COST ($/KW) = 500
ENERGY COST (MILLS/KW-HR) = 10/10

TUBE CONFIGURATION = 6R2P
CONDENSER TYPE = SURFACE
TUBE LENGTH (FT.) = ----
CAPACITY FACTOR = .75
SUMMER HRS NOT EXCEEDED = 29
HOURS ABOVE 82°F AMBIENT = 2760

NOTE: ALL COSTS ARE ANNUALIZED

| | | | | |
|---|---|---|---|---|
| TOTAL COST ($x1000) | 25869 | 25048 | 25097 | 24549 |
| TUBE LENGTH (FT) | 40 | 60 | 70 | 80 |
| MODULE COST ($x1000) | 6433 | 6518 | 6200 | 6224 |
| PIPING COST ($x1000) | 2468 | 2299 | 2200 | 2185 |
| CONDENSER COST ($x1000) | 1058 | 1005 | 1032 | 1008 |
| CAPACITY PENALTY ($x1000) | 11061 | 10607 | 10962 | 10526 |
| ENERGY PENALTY ($x1000) | 1591 | 1488 | 1558 | 1480 |
| INCREMENTAL FUEL COST ($x1000) | 1319 | 1222 | 1283 | 1264 |
| ANNUAL FUEL COST ($x1000) | 45544 | 45447 | 45508 | 45489 |
| NUMBER OF MODULES | 164 | 120 | 96 | 88 |
| TOTAL FAN MW | 21 | 19 | 19 | 20 |
| TOTAL AUXILIARY MW | 29.9 | 27.1 | 28.5 | 29.2 |
| MAX BACK PRESSURE (in.Hga) | 9.3 | 9.1 | 9.3 | 8.9 |
| MAX LOSS IN GENERATION (MW) | 110.6 | 106.1 | 109.6 | 105.3 |
| TTD (°F) | 5.2 | 5.1 | 5.0 | 5.1 |
| ITD.(°F) | 42.6 | 41.8 | 42.5 | 40.7 |
| RANGE (°F) | 17 | 19 | 18 | 19 |

420<

JF

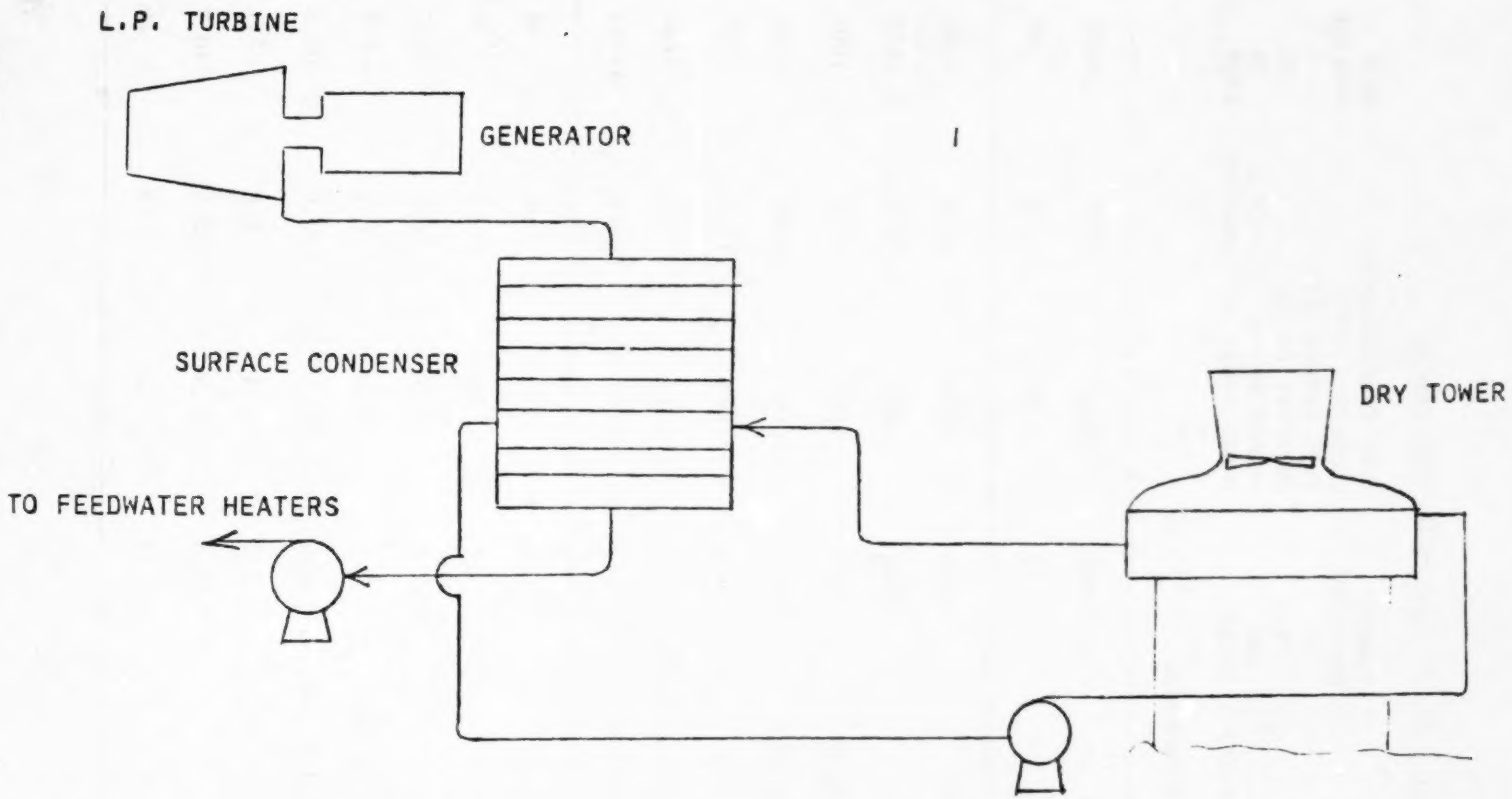

L.P. TURBINE
GENERATOR
SURFACE CONDENSER
DRY TOWER
TO FEEDWATER HEATERS

FIGURE 1

Schematic Diagram of a Dry Cooling System

SITE = CASPER
CONDENSER TYPE = SURFACE
TURBINE TYPE = MOD.CONV.
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = .75
CAPACITY COST ($/KW) = 100
ENERGY COST (MILLS/KW-HR) = 40/20

TUBE CONFIGURATION = 6R2P
CAPACITY FACTOR = .914
SUMMER HRS NOT EXCEEDED = 10
TUBE LENGTH (FT) = 80
ITD = 49.9
RANGE = 28
HRS ABOVE 82°F AMBIENT = 440

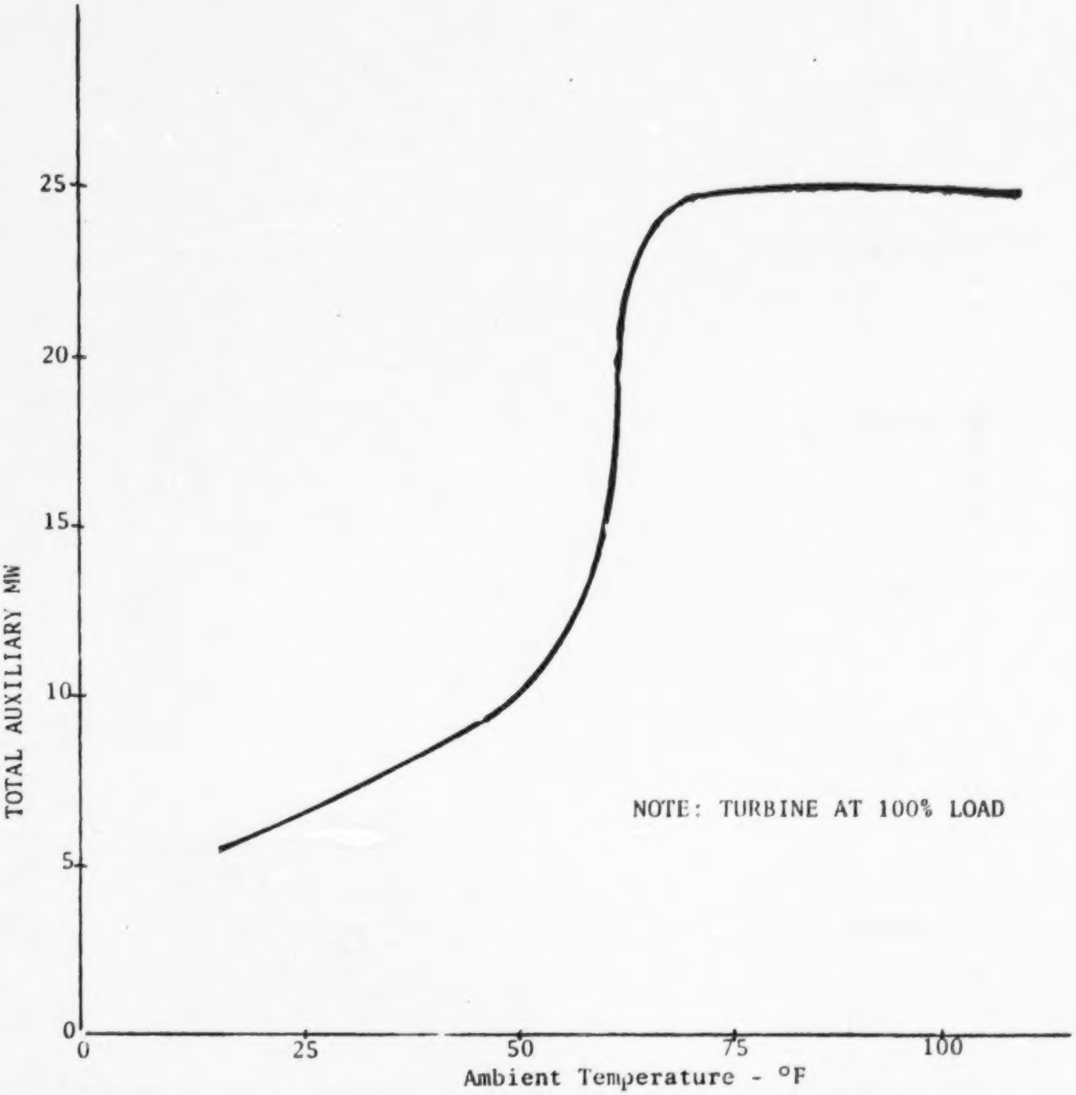
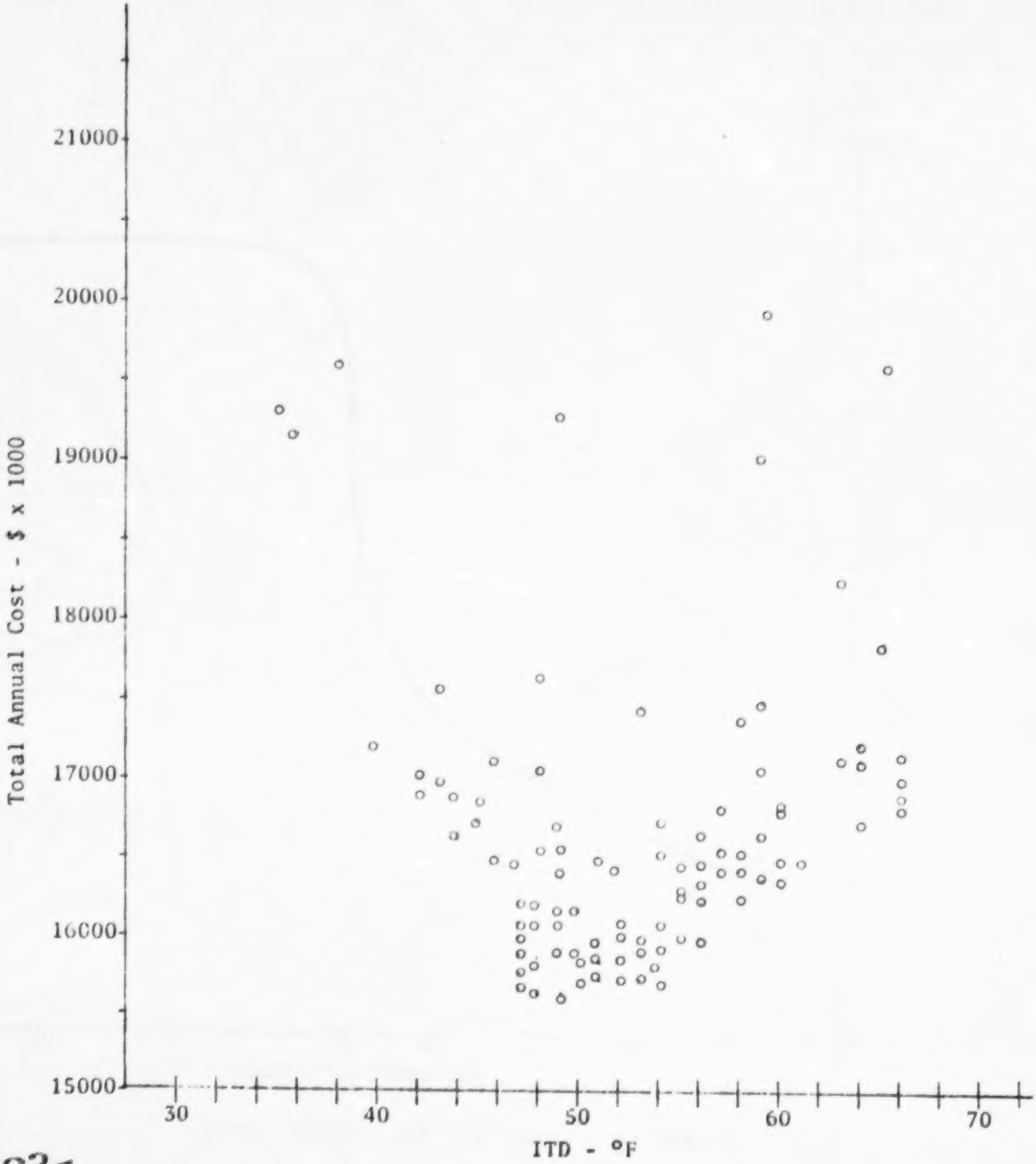


FIGURE 2 TYPICAL FAN CONTROL CURVE

SITE = ATLANTA
CONDENSER TYPE = SURFACE
TURBINE TYPE = MOD.CONV.
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = .75
CAPACITY COST ($/KW) = 100
ENERGY COST (MILLS/KW-HR) = 40/20

TUBE CONFIGURATION = 6R2P
TUBE LENGTH (FT) = 80
CAPACITY FACTOR = .75
SUMMER HRS. NOT EXCEEDED = 29
ITD (°F) = --
RANGE (°F) = --
HRS. ABOVE 82°F AMBIENT = 783

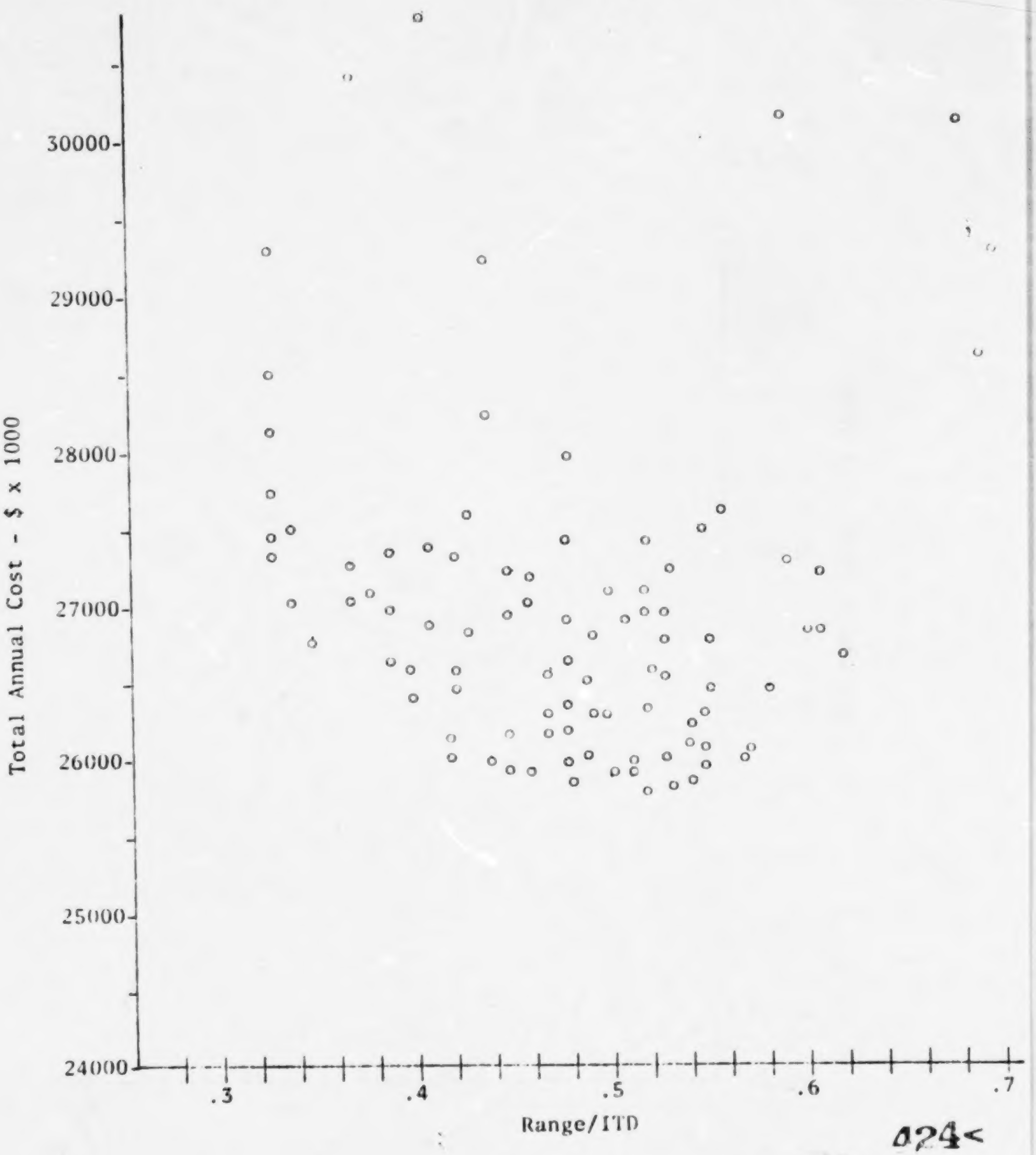


423<

FIGURE 3 - TOTAL ANNUAL COST VS ITD

SITE = PHOENIX
CONDENSER TYPE = SURFACE
TURBINE TYPE = MOD.CONV.
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = .75
CAPACITY COST ($/KW) = 500
ENERGY COST (MILLS/KW-HR) = 10/10

TUBE CONFIGURATION = 6R2P
TUBE LENGTH (FT) = 80
CAPACITY FACTOR = .75
SUMMER HRS. NOT EXCEEDED = 29
ITD (°F) = 30
RANGE (°F) = --
HRS. ABOVE 82°F AMBIENT = 2760



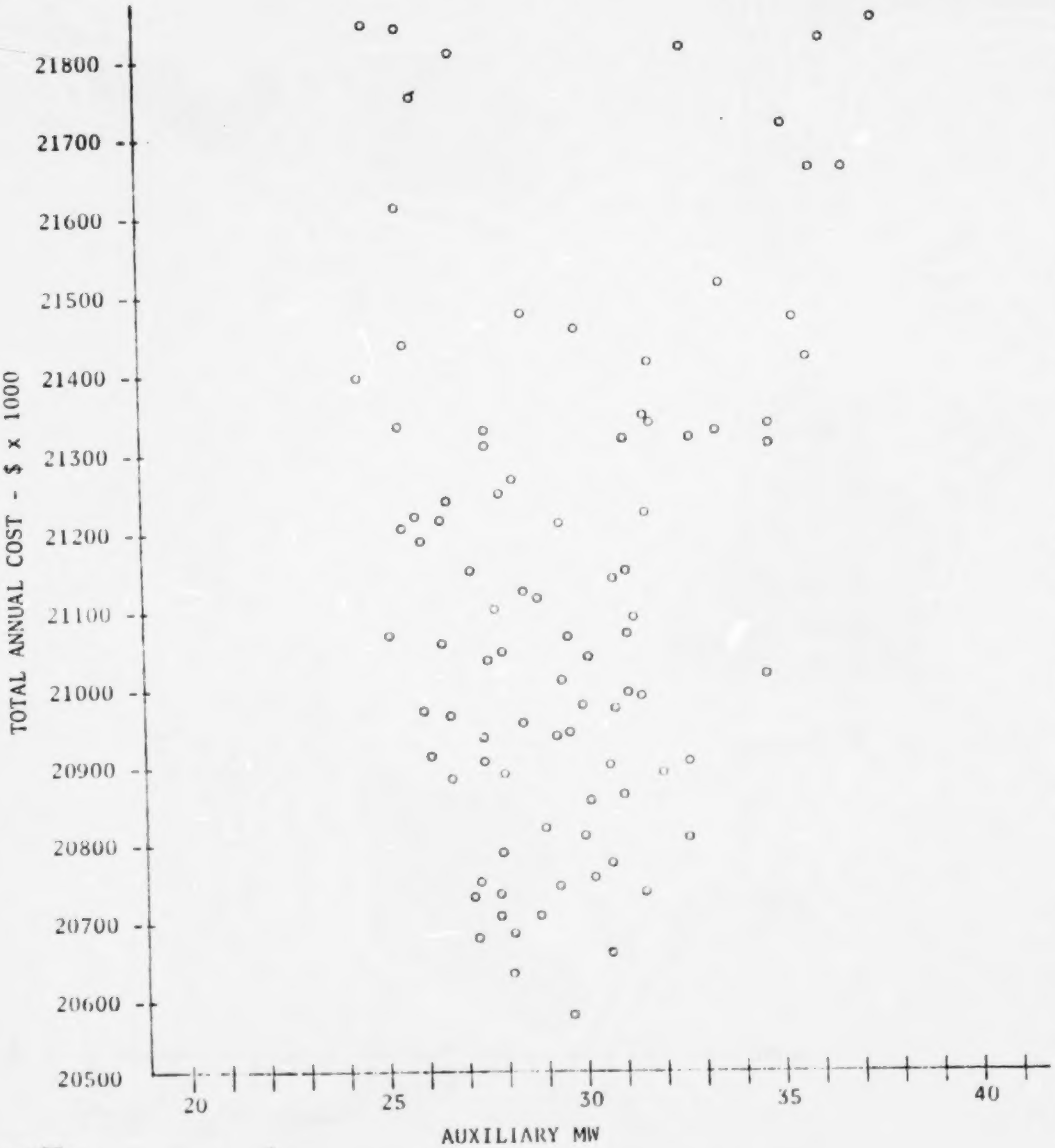
424<

FIGURE 4 - TOTAL ANNUAL COST VS RANGE/ITD

JF

SITE = PHOENIX
CONDENSER TYPE = SURFACE
TURBINE TYPE = MOD. CONV.
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = .75
CAPACITY COST ($/KW) = 100
ENERGY COST (MILLS/KW-HR) = 40/20

TUBE CONFIGURATION = 6R2P
TUBE LENGTH (FT) = 80
CAPACITY FACTOR = .75
SUMMER HRS. NOT EXCEEDED = 10
ITD (°F) = --
RANGE (°F) = --
HRS. ABOVE 82°F AMBIENT = 2760



425<

FIGURE 5 – TOTAL ANNUAL COST VS AUXILIARY MW

JF

SITE = PHOENIX
CONDENSER TYPE = SURFACE
TURBINE TYPE = MOD.CONV.
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = .75
CAPACITY COST ($/KW) = 500
ENERGY COST (MILLS/KW-HR) = 10/10

TUBE CONFIGURATION = 6R2P
TUBE LENGTH (FT) = --
CAPACITY FACTOR = .75
SUMMER HRS. NOT EXCEEDED = 29
ITD (°F) = 41-43
RANGE (°F) = --
HRS. ABOVE 82°F AMBIENT = 2760

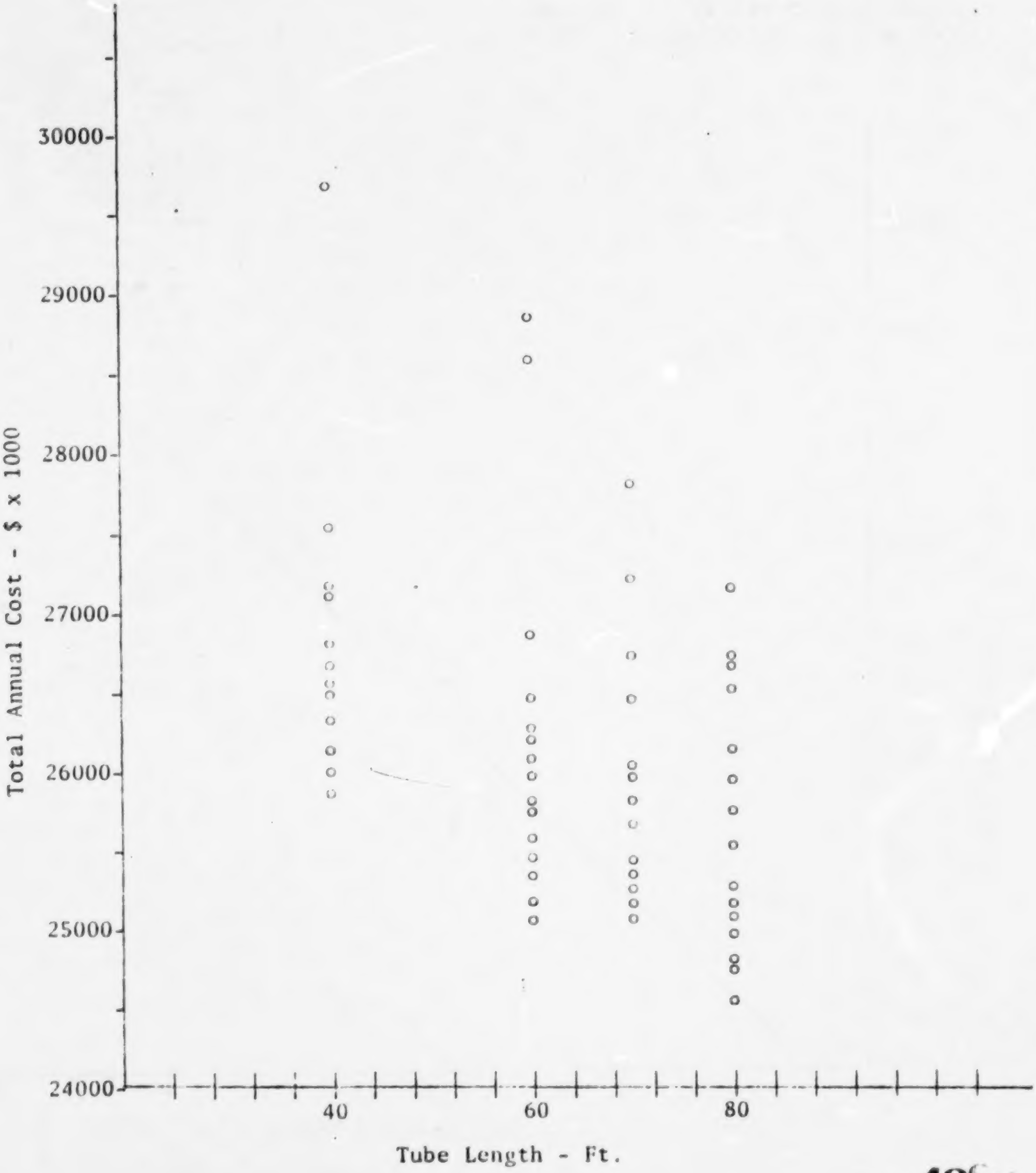
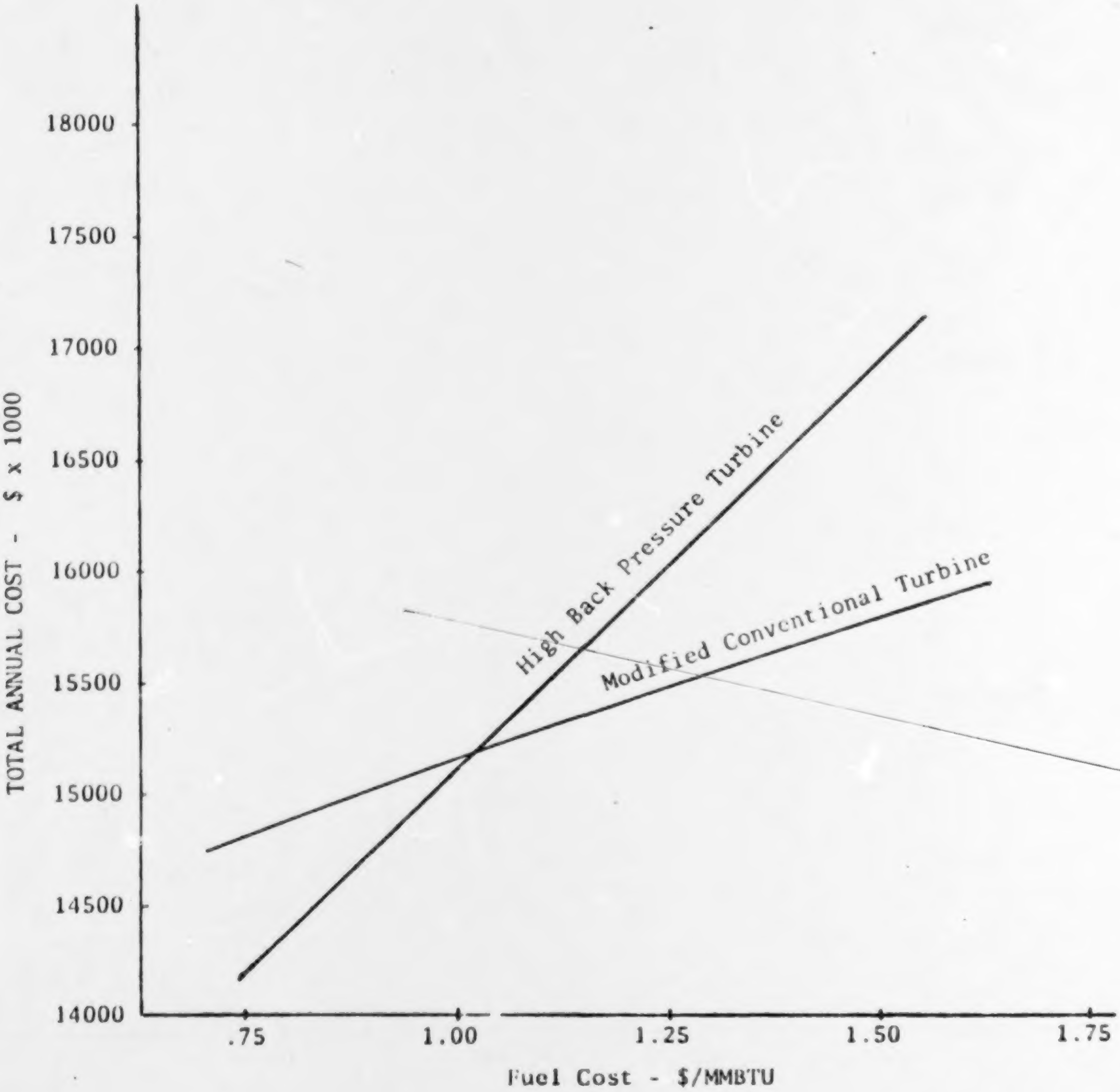


FIGURE 6 - TOTAL ANNUAL COST VS TUBE LENGTH

| | | | |
|---|---|---|---|
| SITE = CASPER | | TUBE CONFIGURATION = 6R2P | |

SITE = CASPER
CONDENSER TYPE = SURFACE
TURBINE TYPE = ----
FIXED CHARGE RATE = .20
FUEL COST ($/MMBTU) = ----
CAPACITY COST ($/KW) = 100
ENERGY COST (MILLS/KW-HR) = 40/20

TUBE CONFIGURATION = 6R2P
CAPACITY FACTOR = .75
SUMMER HRS NOT EXCEEDED = 29
TUBE LENGTH (FT) = 80
HRS ABOVE 82°F AMBIENT = 440



427< FIGURE 7 - TOTAL ANNUAL COST VS FUEL COST

JF